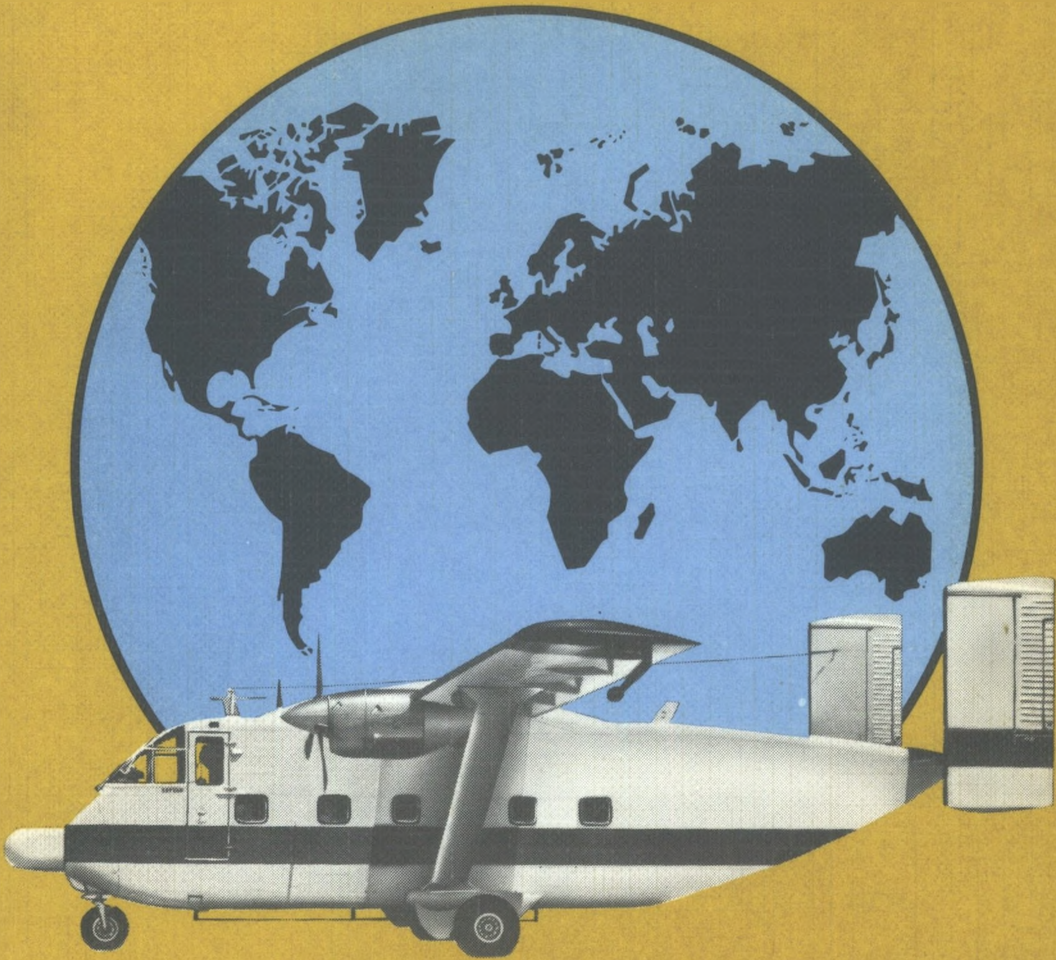

PROCEEDINGS OF A PANEL, VIENNA, 10-14 APRIL 1972

Uranium Exploration Methods

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1973

URANIUM EXPLORATION METHODS

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URANIUM EXPLORATION METHODS

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INTERNATIONAL ATOMIC ENERGY AGENCY
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NOTE

In these Panel Proceedings, the costs given in US dollars refer to April 1972 and changes in dollar rates since then have not been taken into account.

URANIUM EXPLORATION METHODS
IAEA, VIENNA, 1973
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FOREWORD

Forecasts of uranium requirements up to the end of the present century show a very large and increasing annual demand from the late 1970s onward. Although recent discoveries and the present substantial reserves have induced a current surplus situation, the longer-term requirements for uranium is very great. There is at present a tendency to cut back exploration, but most authorities believe, on the contrary, that this is the time for planning to intensify uranium exploration.

Over 90% of the present low-cost uranium reserves are concentrated in five major uranium countries; but considerable areas of the world, geologically favourable for the occurrence of uranium, remain to be explored in developing countries.

In 1970 the International Atomic Energy Agency convened a Panel in Vienna on 'Uranium Exploration Geology', the proceedings of which were published the same year under that title in the Panel Proceedings Series. The philosophy of that Panel was that, in any exploration effort, understanding the mineralogy and geological occurrence of uranium is a basic requirement. The Panel, therefore, discussed concepts of the regional, tectonic, lithological and geochemical distribution of uranium and also the criteria necessary to indicate areas of the world which may be favourable for the occurrence of new economic deposits.

Agreeing that 'uranium exploration geology' covered only half the subject, the 1970 Panel recommended that a complementary Panel on 'uranium exploration methods' would serve a very useful purpose. As a result, the Agency convened a Panel in Vienna from 10 to 14 April 1972 with the objectives of reviewing available information on uranium exploration methods and formulating recommendations on future research and development of techniques. The requirements of developing countries were also considered, including policy, types of programs, costs, and the application of the most appropriate exploration techniques to specific environments.

Uranium exploration geologists from various parts of the world, with experience in using different types of exploration techniques, participated. The Agency is grateful to all those who contributed papers, took part in the discussions and helped to prepare the Panel Reports on specific subjects. Thanks are especially due to the Chairman, Dr. S. H. U. Bowie, Head of the Geochemical Department, Institute of Geological Sciences, London, who guided the work of the entire Panel, and also to the Chairmen and members of the Panel sub-committees.

CONTENTS

INTRODUCTORY REVIEW

URANIUM EXPLORATION POLICY, ECONOMICS, AND FUTURE PROSPECTS

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United States of America

Abstract

URANIUM EXPLORATION POLICY, ECONOMICS AND FUTURE PROSPECTS.

Presently known low-cost uranium reserves are about equal to anticipated requirements into the 1980s. Intensive exploration will be necessary to meet the increasing demand later in this century. World-wide exploration has declined in most areas as a consequence of low uranium prices, but long lead times and uncertainties concerning exploration success indicate the need to resume vigorous exploration soon. The uncertainty is emphasized by the fact that only about 20 areas of the world have so far been found to contain deposits of a size that is economically attractive. The magnitude of the effort needed is emphasized by the fact that several thousand million dollars must be spent in the remainder of this century in exploration for uranium which will have a value in the tens of thousands of millions of dollars. Many potentially favorable areas remain to be explored, and a number of the less developed countries have undertaken or are considering uranium exploration programs. The money and technical manpower required often make it attractive for developing countries to use assistance from IAEA, from other countries, or from private companies as concessionaires, contractors, or as partners. In every case, it is desirable to have an indigenous geological staff capable of evaluating developments and providing technical advice to the government. Uranium exploration programs are more likely to be successful if they are oriented towards identification and evaluation of resource areas containing at least several thousand tons of uranium. Exploration teams using a number of skills and sophisticated equipment can assess large regions and selectively reduce targets to drilling projects of a few hectares. Such exploration programs may cost $1 million annually for several years. Total capital investment of around $20 million and a period of 8 to 10 years may be required for a successful project from inception to production. Details of typical exploration programs and costs are described.

1. INTRODUCTION

The Panel on Uranium Exploration Methods was held on the recommendation of the Panel on Uranium Exploration Geology which convened in Vienna two years ago. It has been charged by the International Atomic Energy Agency with the objective of "reviewing available information on uranium exploration methods, formulating recommendations on future research and development of techniques, and studying the policies and exploration requirements which can be recommended to developing countries." It is entirely fitting that these matters be considered at this time in view of the impending need for additional sources of uranium.

Before the end of this century, the cumulative demand for uranium will have increased to five or six times the total quantity that has been produced to date. This estimated cumulative demand and the resources now estimated are shown in Fig. 1. The task of discovering the estimated additional uranium will be formidable and the costs involved in exploration alone will be measured in the thousands of millions of dollars.

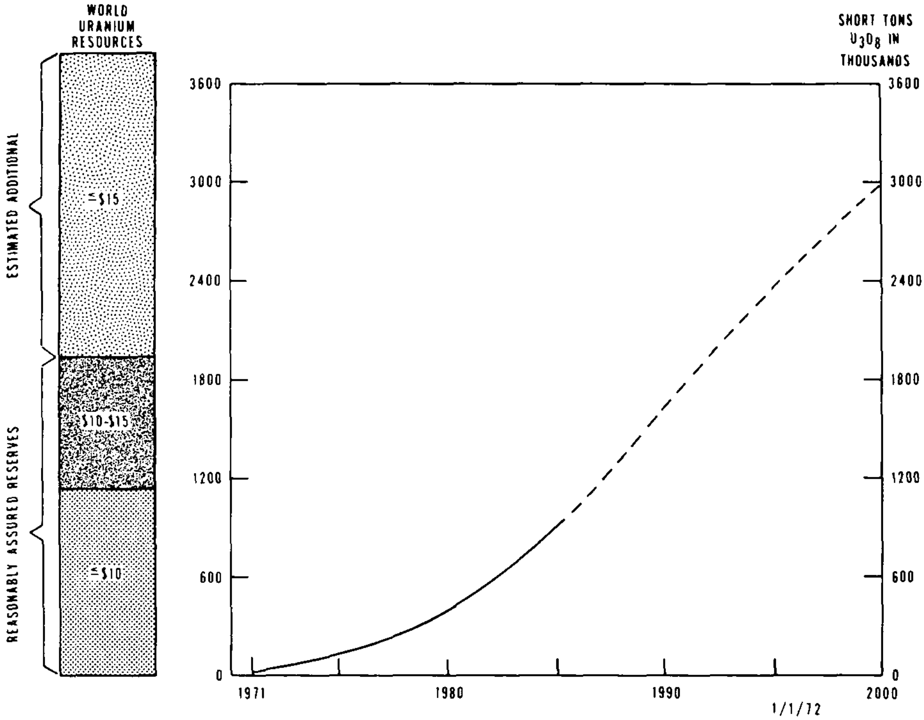

FIG. 1. World cumulative uranium requirements, not including the socialist countries, through the year 2000. (Assumes breeder reactors introduced in the late 1980s). Through 1985: USAEC forecast, Rep. WASH 1139; from 1986 to 2000: estimated requirements after M. Davis, J. Br. Nucl. Energy Soc. No.2 (1968).

At present, there is a soft uranium market which is the result of slippage in nuclear fuel requirements. As a consequence of this slippage, the near-term demand for uranium is essentially filled, prices are low, and the incentive to continue exploration has diminished considerably. This is unfortunate, because the search for uranium should be expanded to provide the reserves needed to meet future requirements. There is good reason to think that much more uranium can be found if a high level of well-planned exploration is carried out. The problem is to find it on a timely schedule without crash programs that increase costs, create supply risks, and cause problems in planning and utilization of nuclear power.

The variety of geological environments in which uranium occurs is encouraging. There is already a substantial body of geological information which has contributed considerably to our understanding of the conditions that govern uranium deposition, particularly in sedimentary environments. However, the problems of uranium geology are by no means resolved. It is important therefore that uranium exploration continue to be accompanied by an effort to identify and understand the circumstances that favor its deposition. The rewards of such efforts have already been demonstrated by exploration in the United States of America, where a few well-established concepts have been used successfully. The prospects for discovery in new and untested environments should also be examined, and research should be aimed at developing and testing new geological concepts.

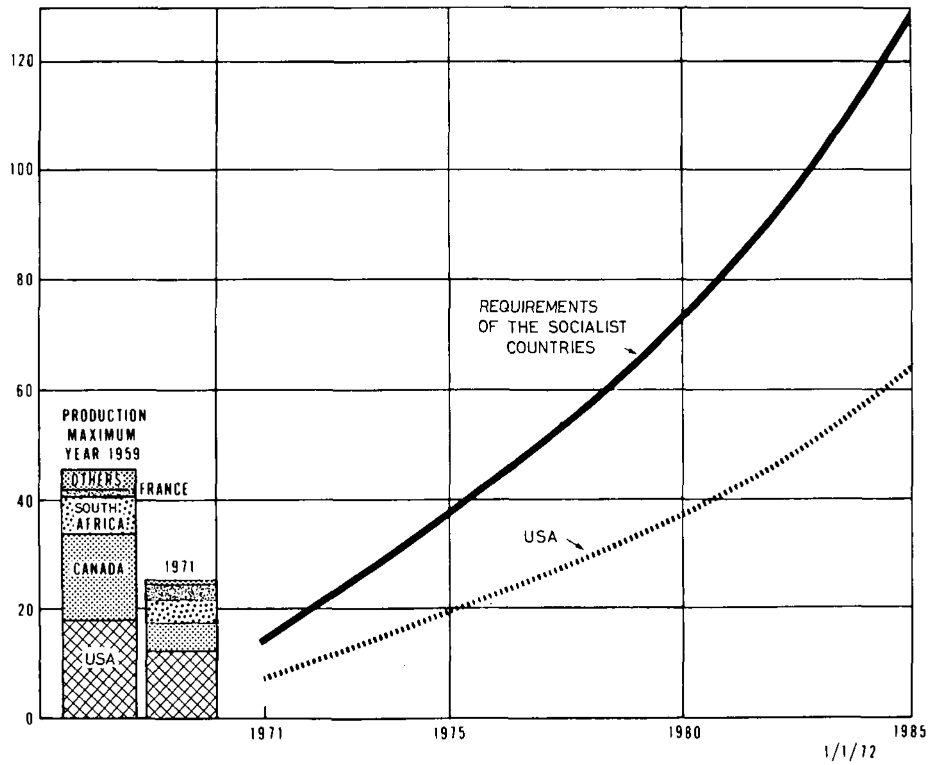

FIG. 2. Annual uranium requirements and production (thousands of short tons U_3O_8).

2. URANIUM REQUIREMENTS, RESOURCES AND PRODUCTION CAPABILITY

The present annual world requirement for nuclear fuel, excluding the socialist countries, is about 16 000 t of U_3O_8 (Fig. 2). An eightfold increase to about 130 000 t/yr is expected by 1985, by which date cumulative requirements will have reached 900 000 t (Fig. 1). The need for uranium will continue to increase beyond 1985 until breeder reactors begin to provide some relief. To provide for those additional needs, a reserve about equal to the requirement of the following eight years should be maintained. This would be 1.0 to 1.5 million tons of U_3O_8.

Against this demand, there is a current reserve of about 1.1 million tons of low-cost uranium, i.e., costing less than U.S. \$10/lb of U_3O_8 (Fig. 3). This quantity is about equal to requirements through 1986, but because of production limitations it may not support the demands projected through the 1970s. Discovery and development of estimated additional uranium resources "surmised to occur in unexplored extensions of known deposits or in undiscovered deposits in known uranium districts" [1] could add one million tons of U_3O_8, extending the availability of low-cost supplies through the 1980s.

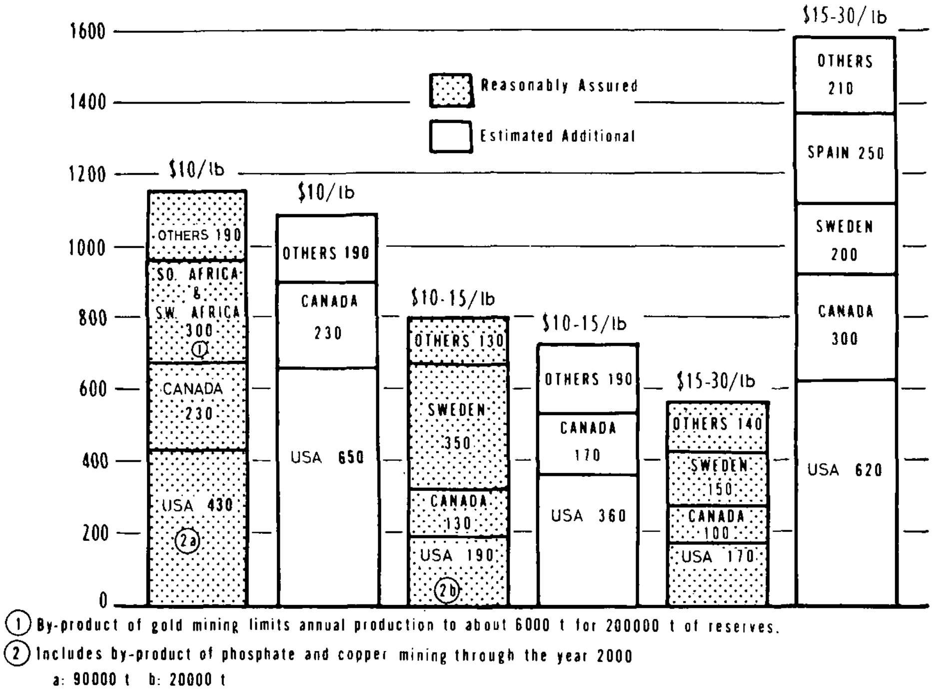

FIG. 3. World uranium resources (thousands of tons U_3O_8). China, USSR and Eastern Europe not reported.

Current world production capability is around 30 000 t of U_3O_8 annually, about double current demand. By 1980, however, annual production capability that can be expected from presently known resources will be well below the forecast demand. Thus there is a need not only for exploration but also for timely development of new production facilities. This is further complicated by the fact that production capability is restricted in some instances even where reserves are large. South African uranium production, for example, is limited by the rate of milling of uraniferous gold ores, and Canadian production is limited to the capability to produce from a few large mines.

3. CURRENT AND PROSPECTIVE SOURCES OF URANIUM

Only nine countries of the world, excluding the socialist countries, have produced as much as 1000 t of U_3O_8. Reserves of more than 1000 t of U_3O_8 at US $10/lb are known in only 17 countries (Fig. 4), of which 12 are now producing. As noted in Fig. 5, most of the world's known reserves are concentrated in only a few countries – 94% in the seven countries listed. These reserves are divided almost equally among three types of deposits, the quartz pebble conglomerate deposits of South Africa and Canada, the sandstone-type deposits of the United States and Niger, and the vein and other non-bedded deposits of Europe, Canada, Australia, and South West Africa (Fig. 6).

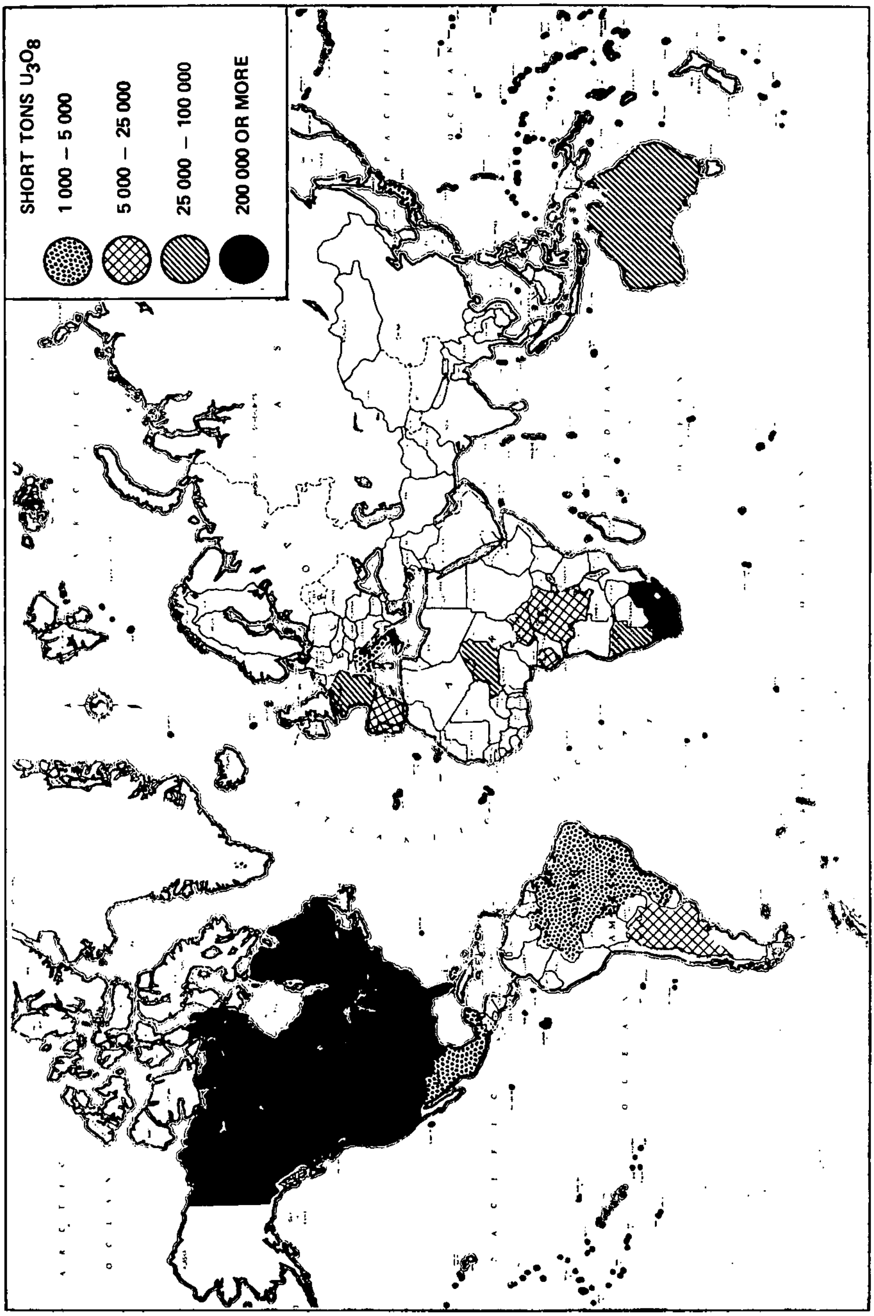

FIG.4. World uranium resources. Reasonably assured reserves at \$10/lb U_3O_8. China, USSR and Eastern Europe not reported.

	TONS	%
USA	430 000	37
South Africa & Southwest Africa	300 000	26
Canada	232 000	20
France	41 000	4
Niger	26 000	2
Australia	50 000	5
Other	71 000	6
TOTAL	1 150 000	100

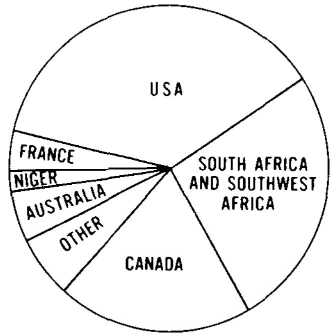

FIG. 5. World uranium reserves at \$10/lb U_3O_8 (short tons U_3O_8). China, USSR and Eastern Europe not reported.

	TONS	%
Conglomerate	380	33
Sandstone	390	34
Veins & Other	380	33
TOTAL	1150	100

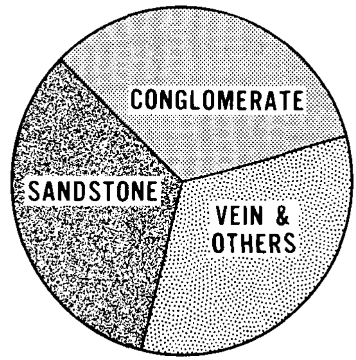

FIG. 6. World uranium reserves of \$10/lb U_3O_8 by host rock (thousands of short tons U_3O_8). China, USSR and Eastern Europe not reported.

Other potential sources of uranium can be drawn upon in addition to known reserves. An estimated 90 000 t of U_3O_8 could be recovered in the United States as a byproduct of phosphate and copper production by the end of this century. An additional 800 000 t of U_3O_8 is estimated in the reasonably assured category if the price of uranium were to be increased to \$15/lb. However, half of this higher-cost material is in Swedish black shales and, according to Swedish authorities, production from this source will be restricted to helping meet only Sweden's needs. Because of the long lead time needed to develop any large low-grade deposit, and the prevailing low prices which will probably not exceed \$10 for the next decade, substantial production cannot be expected from such sources during the next 20 years when requirements will be largest. Discovery of new low-cost resources appears to be the only reasonable alternative for meeting future requirements.

Fortunately, there are extensive, apparently favorable areas that have not yet been prospected. Although many of these are remote, the obstacles to exploration can probably be surmounted in much the same manner as they have been in the development of the Niger deposits. Undoubtedly, future exploration will continue to focus on Africa and on Australia where important new finds have recently been made.

4. EXPLORATION ACTIVITY

In anticipation of a commercial market, large-scale exploration for uranium resumed in the United States in the late 1960s. The peak was reached in 1969 when a record 9 000 km of drilling in 76 000 holes averaging 120 m deep was achieved. Although no new districts were found, several known areas were extended. During 1969, 1970, and 1971 about 170 000 t of U_3O_8 (recoverable at $10/lb) were added to United States reserves.

Since 1948, 54 500 km of surface drilling has been completed in the United States, adding 560 000 short tons of U_3O_8 to $10 reserves (excluding byproduct uranium). This is equivalent to an average discovery rate of 6.3 lb/ft or 0.9 kg/m drilled. In 1971, drilling dropped to 15 500 000 ft as a result of weakening uranium prices and filling of the near-term market. Uranium exploration also declined world-wide in 1970 and 1971, except in a few countries, notably Australia.

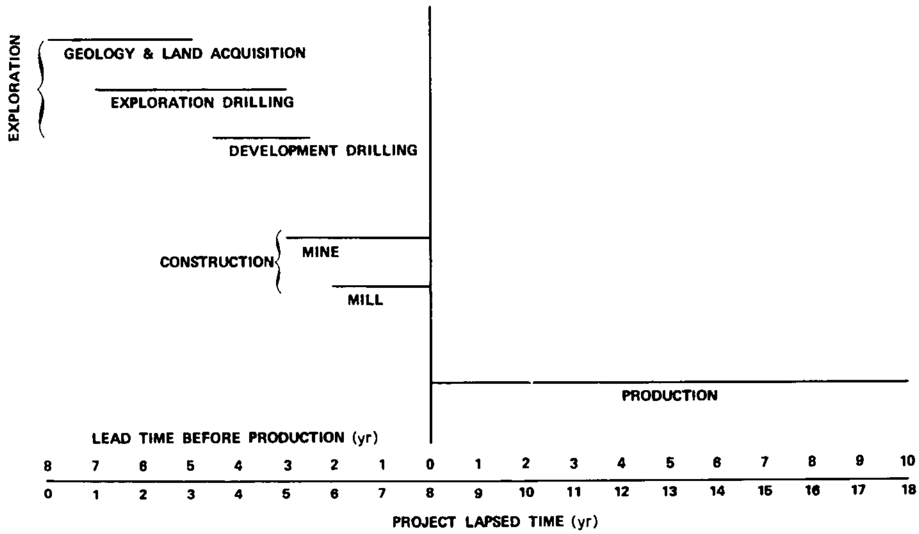

FIG. 7. Typical activity time-scale of uranium production facility.

Experience in the United States indicates that the interval between initial exploration and production may range from 3 to 10 years. An 8-yr lead time is probably typical (Fig. 7). This includes about three years for acquisition of geological data, area selection and land acquisition, four years of exploration drilling and two years of development drilling, followed by three years for mine development and mill construction. These phases are not independent but overlap in time. Development drilling may grade into and overlap exploration drilling, and mine development may begin before development drilling is completed. Exploration lead times can be shortened by experienced field staffs and larger programs, thus enabling production to begin earlier.

5. EXPLORATION POLICY

Alternative means of carrying out uranium exploration and development programs have been discussed by Cameron [2]. In some countries the national geological survey or bureau of mines participates while in others the responsibility rests with a uranium raw materials group established within a national atomic energy organization. Many developing countries with limited capabilities find it advantageous to obtain assistance from mining companies with experience in uranium exploration and risk capital. Such arrangements may be mutually beneficial if entered into with sound planning and clearly established lines of technical, fiscal and administrative authority and responsibility. Since operating capital and staff are frequently supplied by the company, national resources of money and manpower are not strained. In addition, such arrangements often provide an opportunity for training in exploration and mining skills.

Developing countries may find it desirable to establish a geological staff within a government raw materials agency at an early stage of resource development to provide familiarity with exploration and mine development activities and the capability to evaluate exploration results in the light of national requirements. Individuals assigned this responsibility should be capable geologists familiar with their country's natural resources and policies. They may find it useful to broaden their knowledge of uranium exploration and exploitation through visits to countries having considerable uranium production experience.

6. EXPLORATION TECHNOLOGY AND COSTS

Most major uranium districts exhibit anomalous surface radioactivity as well as other manifestations of mineralization which serve as guides to ore. These characteristics form the basis for selecting the methods to be used in exploration. The techniques used and the extent of their application will, of course, vary from one geological environment to another and will depend to some extent on the characteristics of the deposits.

Exploration is commonly divided into three phases:

(1) Broad regional reconnaissance. This involves reconnoitering areas of tens of thousands of square kilometers or more to define the more favorable localities in which to concentrate further effort.

(2) Detailed local reconnaissance. This seeks to confirm the favorability of selected areas and to develop information needed for further assessment. Some drilling is usually involved. Areas range from tens to hundreds of square kilometers.

(3) Physical investigation of the more favorable localities by trenching and drilling to (a) discover a deposit, (b) evaluate its size, shape, geological character and value, and (c) facilitate planning for mine development. Areas rarely exceed a few square kilometers.

In the regional reconnaissance phase, aerial radiometric surveying is usually the preferred method. This may be supplemented by simultaneous measurement of magnetic and electromagnetic properties, with photographic coverage for topographic information and for outlining alteration patterns.

Aerial surveying is generally economically attractive for evaluating areas of 1000 km^2 or more. The method becomes increasingly advantageous as the area increases, particularly if time is limited.

Establishing an aerial radiation surveying capability may take from a few months for a simple gross-count radiometric system to three or four years for a more sophisticated gamma spectrometric mapping system. This includes acquisition of equipment, personnel training, computer programming, equipment testing and preparation of supporting functions such as data reduction and analysis.

The cost of operational aerial surveying systems ranges from about \$40 000 to \$400 000. This expense can only be justified by long-term use of the equipment. As an alternative, radiometric surveying services can be obtained under contract. Contract costs generally range from about \$4 per line km for preliminary gross-count reconnaissance to \$20 per line km for sophisticated spectrometric mapping. In the long run, sophisticated aerial surveying might prove less costly if it reduces the need for and expense of follow-up evaluation on the ground. Geophysical-geological reconnaissance, including aerial surveying and preliminary ground checking, can be accomplished for less than \$40/km^2 to \$50/km^2. Under optimum conditions, where anomalies are easily discernible and the geology is simple and well exposed, reconnaissance may cost half this amount. Thus, the cost of covering 50 000 km^2 might range from \$1 000 000 for a gross-count survey to \$2 500 000 for a more sophisticated geophysical-geological evaluation.

The second phase of exploration is generally accomplished by surface geological and geophysical surveys. Although radiometric methods are again extensively used, geological observation and investigation of indications of mineralization become an important component. Some drilling may be done to supplement these studies.

Geological reconnaissance mapping is also undertaken in phase (2) to determine the distribution of mineralization and of radiometric anomalies and their relationship to lithological and structural trends. The stratigraphic, structural, and physiographic history of the area is deciphered to improve understanding of the distribution patterns of the anomalies. As guidelines are developed and the habit of mineralization emerges, physical exploration may proceed more effectively.

Gross gamma-counting equipment is ordinarily employed in surface reconnaissance. Portable scintillation counters satisfactory for this purpose cost about \$1000. Several hundred locations within an area of a square kilometer can be measured and plotted in a day using hand-held equipment. For large areas, vehicle-mounted instruments costing from \$5000 to \$8000 are sometimes used. In easily navigable terrain, vehicular traverses of 50 to 300 line km/d are possible, including map plotting and evaluation. Portable and vehicle-mounted spectrometric instrumentation is also available at a cost of \$3000 to \$15 000, respectively. This equipment can provide a measurement of the uranium, thorium and potassium ratios in rocks, but the data are not strictly quantitative. These data are generally more useful than gross-count data and may reduce the need for chemical assays in the early stages of exploration. Although field experience with surface spectrometric equipment is limited, and costs have not been adequately determined, it is probable that each three-element measurement with data reduction and evaluation will cost about \$3 to \$6.

Radon emanometry surveys have also proved valuable in the intermediate reconnaissance phases of exploration. Techniques include (a) extraction of radon from soil and water, followed by alpha counting, (b) extraction of radon and delayed gamma counting, (c) in-hole total alpha counting, and (d) in-place total alpha measurement by track-etch methods. Radon surveys are best applied to limited areas which have been selected on the basis of other reconnaissance methods and they are not generally recommended as a primary exploration method. Spacing between sample stations, although varying with geological conditions, generally ranges from 10 to 100 m. With simple equipment, 100 or more measurements can be obtained per day under favorable conditions at a cost of about $1 per measurement. With more sophisticated instrumentation, 10 to 25 measurements can be made per day at proportionately higher cost.

Shallow subsurface sampling may be used to supplement surface reconnaissance and it may be accomplished by means of trenching or small hand-portable drills. The portable drills are capable of taking a meter of core if water is available.

Phase (3) involves intensive drilling of the most favorable sites. The project area may cover 10 km^2 or less, perhaps only 1 or 2 km^2. This phase should provide sufficient information to determine the economic value of the discovery and the type and magnitude of a program needed to establish reserves.

Drilling of surface anomalies has not been the most effective means of locating ore deposits in sandstones because the deposits are usually located some distance down dip from the outcrops where anomalies are found. In some areas the ore-bearing beds are not mineralized or anomalously radioactive at the outcrop, and in others they do not outcrop near the deposits. Lisbon Valley, Utah; Ambrosia Lake, New Mexico; and Shirley Basin, Wyoming, are important districts that show little indication of their presence by surface radioactivity. Many sandstone deposits are covered with overburden hundreds of meters thick. Several important deposits occur at depths greater than 500 m, and one currently under development is more than 1500 m deep. As a rule, therefore, radiometric anomalies comprise only one indication of favorability leading to the selection of an area to be drilled.

Emphasis in initial exploratory drilling in sandstones in the United States has been placed, therefore, on identification of favorable geological environments. It is common practice to undertake drilling solely for stratigraphic, lithologic, and mineralogic information. This is done by a combination of rotary drilling, sample recovery and inspection, and geophysical down-hole logging.

Geophysical borehole logging is done with a wide variety of equipment ranging from simple, manually powered, portable units to integrated, vehicle-mounted systems capable of measuring several geophysical properties simultaneously. The latter can record natural gamma, resistance and spontaneous potential measurements in a single hole traverse. Gamma radiation logs and electric logs are the cheapest and most valuable records obtained in exploration drilling. Both provide clues to lithology, and together they improve considerably the geologist's ability to evaluate favorability.

Logging systems cost from $6000 to about $100 000, although usually less than $35 000. Hole logging costs depend largely on how fully the equipment is employed. Costs may be as low as $0.35 to $0.45 per meter

but, if only a few holes per week are logged, the cost may rise to $20 or more per meter. A single truck-mounted logging unit can service two or three rotary drills working locally in consolidated sandstones.

7. EXPLORATION IN NEW ENVIRONMENTS

The easy-to-find uranium deposits in the United States probably have all been discovered, but this may not be true of parts of the world where exploration has been less intense. Discoveries in Australia and Africa are examples of the rewards awaiting those with the courage and insight to do their searching in the relatively untested, remote and less accessible regions of the globe.

To provide assurance against possible shortages of uranium, exploration should be increasingly oriented towards finding new sources of ore outside the currently producing districts. This will probably be more difficult to do in the United States than in other less thoroughly explored regions. To be successful, this effort will require exceptional judgement and insight as well as skilful geological observation and interpretation.

More is known about the factors that govern uranium emplacement and distribution in the sedimentary environment than about depositional controls in other rock types. The success of exploration in sandstones in the United States is attributable in no small measure to the development of an understanding of the ore controls and to the effective utilization of patterns of alteration adjacent to ore as a guide. Because the mineralization processes, as they are now understood, are no different from the normal geochemical processes operating in sandstones in the absence of uranium, the criteria for exploration should be applicable on a world-wide scale. Knowing how these processes operate, it is possible to predict the location of mineralization sites and improve the chances of exploration success. Moreover, the concepts that apply to fluvial sandstones, in which most of the ore in the United States occurs, may also apply to sandstones of marine or aeolian origin, although physical and chemical manifestations may differ somewhat because of differences in the nature and distribution of the ore precipitant.

The geochemical controls that are effective in forming ore deposits at redox boundaries in fluvial sandstones may also be present in the vicinity of salt domes where H_2S has been generated as a result of bacterial action on sulfate and petroleum substrates. They may also apply to gas-water interfaces in or near hidden structural traps and to relict oil fields that are flushed by meteoric waters.

Red/drab/grey interfaces commonly associated with and genetically related to ore in the uranium-producing districts of the western United States occur in other sections of the country. Such color transitions have been observed in the eastern United States, but their significance has not been evaluated.

It might also be rewarding to explore the possibility that uranium deposits have been formed by the mechanisms proposed for the origin of strata-bound copper, lead, and zinc deposits. These deposits occur in a variety of rocks, e.g., shales, limestones, and sandstones. Many mechanisms have been suggested to account for them, and there is no lack of working hypotheses that can be applied to the task.

The value of working hypotheses and concepts has been well demonstrated by uranium exploration in the United States. It may be concluded

from this experience that future research in uranium exploration methodology ought not only to be directed towards development and improvement of instruments and techniques but also towards development and testing of geological concepts.

8. CONCLUSION

The present level of uranium exploration cannot be expected to provide for future needs and must be increased. Rising demand and prices will ultimately provide the incentive for this greater effort, but perhaps not as soon as would appear desirable if the possibility of future shortages is to be eliminated. Thus the development of novel approaches will take on added importance. The exploration effort necessary to satisfy the demand will require an investment of thousands of millions of dollars, skilled manpower, sophisticated equipment, and new ore-guide concepts. The search will be progressively more difficult and expensive. New areas must be investigated which may well include many developing countries. Successful programs can result eventually in much needed income for the national development of such countries. When the investment and technology to carry out adequate exploration programs are beyond their means, such countries may wish to investigate the availability of assistance from international organizations or consider the advantages of bilateral arrangements with other countries or with experienced private mining companies.

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DISCUSSION

D. OSTLE: One of the points by Mr. Nininger is the large number of techniques which can be applied to the different stages of exploration. I wonder to what extent these can be integrated much more at the reconnaissance stage. Mr. Nininger tended to give the impression that the aero-radiometric technique is <u>the</u> method for regional reconnaissance and I would like to solicit some comments on the application of other approaches to the regional reconnaissance stage, including radon, in particular, about which we hear very little in its application to regional investigations, and also geochemistry. Would Mr. Nininger consider it a useful approach to integrate these methods rather than concentrate on aero-radiometric surveys which can be rather expensive, if not soundly based.

R.D. NININGER: Each person in the uranium exploration business in each country obviously sees things in the light of his own experience, and in the United States we have not used as extensively and been so successful with radon and other geochemical methods as has been the case in some other countries. So in my general review I have to admit to a rather

rapid passing-over of that approach. Certainly I know that these are probably approaches that will be successful and have been successful. I would have to say that to the extent to which an organization has the resources to do it, the more approaches that can be used the better.

M. DALL'AGLIO: Unfortunately we have only had experience in Italy but we have applied geochemical prospecting on a regional scale in reconnaissance surveys and we can demonstrate that with such a survey it is possible to search for many elements, that is, uranium, fluorine, mercury, heavy metals and so on, by adopting a low-density grid sampling grid of from five to ten samples per 100 km^2. This kind of geochemical exploration is well suited in our opinion for application in developing countries. Essentially we must accept the general geochemical criteria of searching for many elements in the same survey at the same time.

R.D. NININGER: I would agree with that as there is obviously a multiple advantage in a geochemical prospecting program which may lead you to metals other than uranium. I think one of the things we have had in mind, in emphasizing aerial work, has been the terrain in which we have operated comprising areas of many outcrops in broad sedimentary terrain, desertic-type areas. This has been also true in Central Africa and it has been true in Australia, but this does not mean that geochemical prospecting is not important in certain areas, and perhaps in all areas as either a primary or supplementary approach.

D. OSTLE: I am interested in the extent to which research and development of techniques and application of the results of this R & D is dependent on the role of government agencies and the extent to which private industry enters into this field. Whether, in fact, groups such as this Panel are the sort of driving force behind these developments or whether there is, in fact, very much private work being carried on. What is the situation in the United States for instance?

R.D. NININGER: I think the driving force, as you put it, has been with governments in the past, but I think that as exploration continues there will be more research work done by private industry. Perhaps in our country, where all of the prospecting, or almost all of it, is done by private companies, the major contribution has probably been the development of field techniques through trial and error. Under the conditions that we have, this has provided means by which hidden deposits can be found, but the more long-range research has not been a major effort with most private companies. Now in the new uranium exploration boom in the United States, oil companies with very large financial resources account for about 50% of the total effort and some of these companies are noted for research in oil exploration and are now undertaking and will undertake more research in uranium. We have in our delegation one representative of private industry, Mr. Davis, who might want to comment on this.

J.F. DAVIS: Yes, we do undertake considerable research out of our total budget and I suppose we may be slightly larger than an average company in uranium exploration. About 40% of our budget is dedicated to actual drilling. I would estimate that 20-30% is probably directly or indirectly involved in research. We have done considerable research for instance with drill hole samples on the geochemistry of the pyrites involved. We have experimented with the use of airborne spectrometry versus radon surveying. We have done considerable research in the use of airborne spectrometry in geologic mapping, and in conjunction with the actual dis-

covery we have found that this spectrometry is quite often useful in determining perhaps even the source of the uranium. However, I would say most of our research has been connected with the drill samples which provide probably the most definite means of evaluating uranium potential.

S.H.U. BOWIE (Chairman): Could I ask you a question as to the proportion, if any, of diamond i.e. full-core recovery drilling, that you do as opposed to any other type of drilling?

J.F. DAVIS: We are doing more and more diamond drilling primarily because of the change in our conceptual thinking. As you know, most of the exploration in the USA is primarily sedimentary. I think with the discovery of Narbalek and similar deposits in Australia there has been a shift to increasing exploration for the primary-type deposits. I would say three years ago virtually none of our exploration was diamond drilling, but probably approaching 10% of our drilling is now diamond drilling. That would be on a cost basis rather than a footage basis. Our sedimentary drilling would range from one third of a million to a million feet and about maybe 10 000 to 20 000 feet of diamond drilling per year.

H.H. ADLER: In regard to the question of what technique to use in the initial phases of exploration, I think Mr. Nininger indicated that this was a matter of preference based on individual experience. I gather from discussions with my colleagues in the United States who have been more directly involved with exploration that most, if not all, of the major sandstone-type uranium districts and even the minor ones are represented at the surface by manifestations of anomalous radioactivity and/or spotty mineralization. So that one can, in general, make the statement that our major ore districts were discovered or could have been discovered as the result of surface measurements. I think the prevailing philosophy has been to make your discovery of a new district as rapidly as possible. This consideration stems from the fact that we have many companies competing with each other for discovery of new deposits in the United States, and if one company goes in with sophisticated airborne techniques by which he can make his determinations very rapidly using computerized aid, it is likely to get there much before the company which is still moving on horseback, and you can understand the philosophy of that. Now, I consider radon emanometry for regional appraisal to be a horseback technique compared to the airborne application. It requires detailed inspection of small areas of ground. The sampling is rather slow and tedious and therefore you do not cover large areas as rapidly as one can with the airborne technique. But it does have application at a later stage. We have a division of effort which ranges from rapid extensive coverage to outline a favourable area down to the much more precise definition of where an ore body lies within that area. I think this more or less presents the philosophy of our general approach.

J.F. DAVIS: I might add just a brief comment to that. In looking for new districts we assume that all the outcropping uranium has probably been located in the USA and so we use the philosophy that if we are in a uranium province we actually go out and put down drill holes to look for favourable host rock, alteration or perhaps trace mineralization. We may not have any surface manifestations or even perhaps the host rock may not outcrop but we feel that the combination of favourable host rock alteration and trace mineralization is a sufficiently large target that we can afford to put down some very wild-cat type drill holes on a spacing of perhaps 10 to 20 km.

Y. SHIMAZAKI: Our experience in Japan with airborne radiometric survey has been rather disappointing. I realize it is a rather special case. One reason is the extremely rugged topography and the other is the rather small size of the geology units that we have. So the result of the airborne radiometric survey indicated the differences of geologic units rather than the uranium concentration. Although our experiences are now outdated and there is much more sophisticated equipment available now, we do feel that there are cases where the carborne method is much more reliable and efficient than airborne methods.

R.D. NININGER: With regard to your comments, I think this also indicates what I said earlier – one looks at one's own experience and of course you found your Ningyo-toge deposits by carborne radiometric survey.

D. OSTLE: I think this is obviously a pretty basic question, about the method to be used at the initial stage, and perhaps the Agency is able to comment from the programs they have supported as to whether there is not a danger of dismissing an area as unpromising simply because it has been covered by what is regarded as an effective method. An airborne survey generates a tremendous amount of data requiring follow-up and one also wonders therefore how much data are sitting in files at this moment simply because of an absence of resources to follow them up. Although lacking specific examples I suspect that there are areas which have been flown at enormous cost, which have not presented obvious anomalies leading to an immediate discovery and have been rejected for future work, whereas a combined survey, using other techniques to augment the airborne survey results, might provide more specific indications of uranium occurring in an area. One has to be very sure that, having employed a single technique, the area is not rejected because of a lack of positive results at that stage.

HISTORIES OF NATIONAL PROGRAMS

METHODOLOGY OF URANIUM EXPLORATION IN YUGOSLAVIA*

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Abstract

METHODOLOGY OF URANIUM EXPLORATION IN YUGOSLAVIA.

A short description is given of uranium exploration procedures in Yugoslavia, from analysis of all available geological data to ore reserves calculations and evaluation of ore deposits.

The general area for regional prospecting is the result of preliminary research. After the regional prospecting phase, which is described in more detail, one can outline prospects (in the case of outcropping mineralization) or smaller areas for successive, complex, semidetailed and detailed prospecting. Short descriptions of applied methods in all phases and under different field conditions are given, as well as a possible model of uranium exploration, which is also applicable (in the initial phase, completely, and in the later phases partially) to the exploration of other mineral raw materials.

The most widely used and efficient methods in uranium prospecting are aeroradiometric and geochemical methods. On the basis of Yugoslavian experience, the most efficient method for fast discovery of outcropping uranium deposits is the aeroradiometric method followed by a ground check of the radium-type anomalies obtained, and, in the case of non-outcropping uranium deposits, the most efficient methods are systematic and successive geological, geophysical and especially geochemical exploration methods. The authors also suggest that uranium exploration is just a part of the complex exploration and evaluation of a region for mineral raw materials expected to be found in the region.

* Only the abstract is printed here, as the authors were unable to attend the meeting. However, the paper was open to discussion. Requests for copies of this paper should be addressed direct to the author.

PROGRAMA DE PROSPECCION DE YACIMIENTOS URANIFEROS EN ESPAÑA
Evolución de técnicas y métodos

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Abstract–Resumen

SPAIN'S URANIUM EXPLORATION PROGRAM: DEVELOPMENT OF TECHNIQUES AND METHODS.
In the light of the aims formulated by the IAEA at its Panel on Uranium Exploration Methods, it was thought that it would be of considerable interest to describe Spain's experience in developing exploration programs from the initial stages to the present planning stage. The gradual changes in the guidelines followed in prospecting for radioactive ores have resulted from the experience gained in Spain and in other countries, due regard being paid to geological conditions in Spain, the facilities available and the peaceful uses of this source of energy. These changes have affected the way in which each exploration technique is used (leading to rationalization in the co-ordinated use of different techniques), the scientific considerations underlying the work and the structure and basic organization of the departments involved in uranium exploration. This paper presents significant information on radiometric prospecting (airborne, carborne and on foot), geochemical prospecting, surface studies and studies carried out by means of boreholes, probes and shafts. The paper also describes the main features of Spain's present program and its four-year plan for the immediate future.

PROGRAMA DE PROSPECCION DE YACIMIENTOS URANIFEROS EN ESPAÑA: EVOLUCION DE TECNICAS Y METODOS.
En orden a los fines que se ha trazado el OIEA en la reunión de este grupo de expertos, consideramos de gran interés exponer nuestra experiencia en la evolución de los programas de prospección desde los primeros trabajos efectuados hasta nuestra actual planificación. Los cambios progresivos de nuestras directrices en las tareas de búsqueda de minerales radiactivos, han sido consecuencia del aprovechamiento de nuestra propia experiencia, así como de la que venía produciéndose en los demás países y siempre condicionada por las características propias de nuestras formaciones geológicas, de los medios disponibles y de la utilización para fines pacíficos de esta fuente de energía. Fundamentalmente esta evolución ha afectado tanto al empleo de cada una de las técnicas y la mayor racionalización en el uso coordinado de varias de ellas, como a las ideas científicas que orientaban nuestro trabajo y a la estructura de la organización básica de los departamentos implicados en esta investigación. Por la razón antes citada especificamos en este trabajo cuantos datos positivos creemos que son significativos tanto en las técnicas de prospección radiométrica, aérea, autoportada o a pie, como de la prospección geoquímica y las investigaciones en superficie y profundidad mediante calicatas, sondeos y labores mineras; igualmente se exponen las características actuales de nuestros programas y un esquema de planificación para el futuro inmediato en forma de plan cuatrienal.

1. INTRODUCCION

En orden a los fines que se ha trazado el OIEA en la reunión de este grupo de expertos, consideramos de interés exponer nuestra experiencia en la evolución de los programas de prospección, desde los primeros trabajos efectuados hasta nuestra actual planificación. Condicionantes esenciales para controlar esta evolución y desarrollo, han sido la experiencia obtenida en nuestros propios trabajos y la

producida en los demás países, aparte de las características geológicas de nuestras formaciones favorables y los medios disponibles en cada etapa.

En España existen unas acusadas necesidades previsibles de concentrados uraníferos, para atender a la demanda de energía eléctrica de origen nuclear y unas reservas estimables pero insuficientes a medio y largo plazo, aparte de unas perspectivas fundadas de poder ampliar las mismas.

Estas condiciones nacionales, unidas a que las reservas conocidas son limitadas también, llevan a la conclusión inmediata de que está plenamente justificado el realizar el esfuerzo que sea necesario para terminar de poner en evidencia una materia prima absolutamente necesaria para completar nuestro proceso de industrialización.

2. EVOLUCION DE LOS METODOS DE TRABAJO

El esfuerzo de prospección que hubo necesidad de emprender por todo el mundo, a partir de 1945, no pudo apoyarse - en los primeros momentos - en un conocimiento a fondo de la geología y la metalogenía del uranio. La información básica disponible a partir de los yacimientos beneficiados para el radio, era insignificante e incompleta y esto explica los pasos vacilantes de los primeros tiempos, con errores de concepto importantes. Ejemplo de esto que decimos, fue la desmesurada atención que se dedicó a las pegmatitas en todo el mundo (incluidas las nuestras de Sierra Albarrana), como posible roca capaz de alojar yacimientos uraníferos importantes.

Se realizó un esfuerzo considerable desde los primeros momentos, aún sin una apoyatura técnica y científica adecuada. Este trabajo fue facilitado por unos aparatos Geiger muy rudimentarios todavía, pero que significaban una eficacia notable, desconocida hasta entonces, en la búsqueda de otros metales no radiactivos.

En una primera época se buscaban - y encontraban - anomalías y yacimientos ligados a la superficie del terreno, a pesar de no disponerse nada más que de técnicas muy simples, incluso elementales.

El hecho de que, efectivamente, se partiera casi de cero en lo que se refiere a conocimientos geológicos y metalogénicos, no quiere decir que no se avanzara muy rápidamente en estos estudios, como se demostró en la primera conferencia de Ginebra en 1955, donde comenzó a aparecer una abundantísima información científica en relación con los yacimientos uraníferos.

La evolución experimentada en los últimos 25 años por los métodos de prospección e investigación, viene condicionada por un cada día mejor conocimiento geológico a escala local y regional donde se desenvuelven estos trabajos y por la necesidad - cada día más acentuada - de poner a punto un dispositivo adecuado para encontrar los yacimientos no aflorantes, donde la radiometría tiene poca o ninguna significación.

Por todas las etapas indicadas se ha pasado, en lo que respecta a la prospección del uranio, en nuestro país. En cada momento, se ha dedicado la atención que se ha creído más justificada a los distintos tipos de terrenos: desde los pegmatíticos a los granitos, y de éstos, a los metasedimentos más o menos próximos al contacto, para terminar en el

sedimentario de origen continental. Simplemente, el centro de gravedad se ha ido desplazando, desde los terrenos afectados por la orogenia hercínica, hasta los terrenos sedimentarios, especialmente mesozoicos y terciarios, de origen continental.

Con esto no queremos significar que hayan perdido todo su interés los primeros, que son donde han aparecido nuestras actuales reservas, tanto en lo que queda por ver de los terrenos graníticos y metamórficos, como en el necesario repaso que habrá de realizarse en ciertas zonas relacionadas con ellas y que se habían dado por vistas. Simplemente queremos señalar que se está sistematizando la prospección del sedimentario, que presenta caracteres suficientemente favorables en este país y que está más retrasado en su investigación.

Toda la problemática que presenta la prospección de yacimientos en sedimentario, se complica por el hecho de que – salvo algunas excepciones que se han dado – no existe una relación de cercanía entre los indicios superficiales y los verdaderos cuerpos mineralizados, si existen.

Esto exige llevar, durante la misma prospección y durante todas las etapas de la investigación, un estudio geológico fino y recurrir a técnicas de empleo no corriente en las otras minerías, pero sí en la industria petrolera. La geoquímica, la paleogeografía, la sedimentología, la geofísica, técnicas muy sofisticadas en el registro de los sondeos y el tratamiento de los miles de datos obtenidos en computadoras, son de uso normal ya.

El empleo juicioso de las mismas, y el empleo masivo de un instrumento caro como son los sondeos, que han de ser mucho más numerosos y profundos, suponen una preparación y unos riesgos de pérdidas que sólo pueden ser aceptados por grandes empresas privadas u organismos gubernamentales que emplean medios poderosos.

Por todo lo que llevamos dicho hasta ahora, resultan evidentes las sustanciales diferencias que existen entre las condiciones que se dieron en los primeros tiempos de la prospección uranífera y en las que estamos obligados a desenvolvernos actualmente. Y toda esta evolución se ha producido en el corto espacio de tiempo de 25 años, lo cual evidencia lo que dijimos al principio, y es la juventud y, a pesar de eso, la madurez de la industria minera del uranio.

3. ORGANIZACION DE LA DIG Y MISIONES DE LOS DISTINTOS DEPARTAMENTOS

La DIG, que consta de unas 175 personas, se puede desglosar en tres conjuntos esenciales: jefatura, con un 6% de efectivos en cuanto a personal se refiere, un 22% integrados en las técnicas auxiliares y un 72% que abarca a los que trabajan sobre el terreno. En el momento actual, de este último gran bloque sólo un 44% realiza labor de cobertera para el hallazgo de indicios en el terreno, fundamentalmente mediante radiometría. El 28% restante está dedicado a la investigación de los indicios y evaluación de yacimientos. El 44% antes citado constituye además un fondo de reserva, del que se extrae personal para investigación, si los resultados de la cobertera son suficientemente alentadores. Nuestra preocupación frente al próximo plan cuatrienal, consiste en

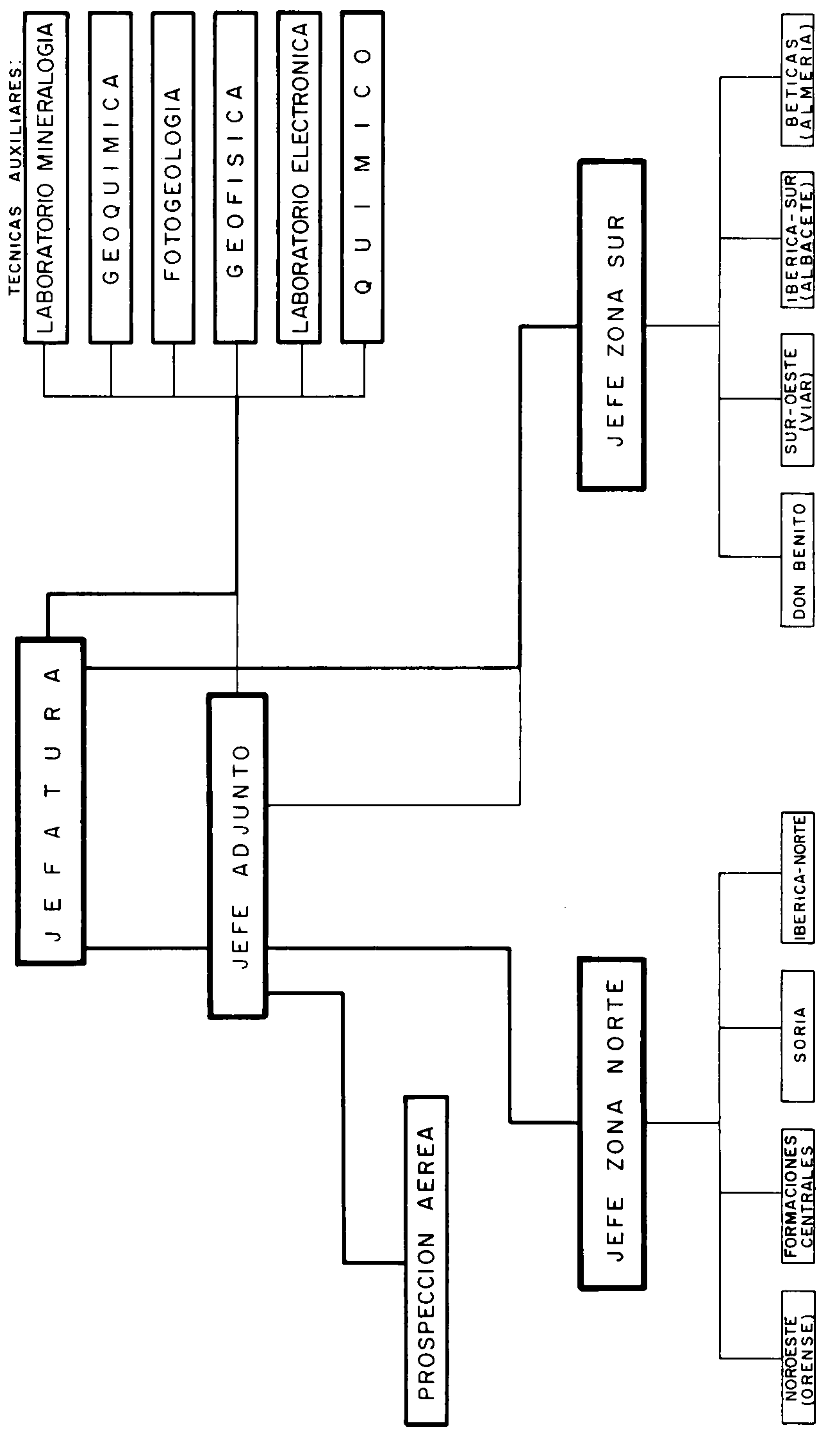

FIG.1. Organigrama de la División de Investigación Geológica.

poder aumentar en lo posible el gran bloque del 72% para evitar el que, al quedar inmovilizados muchos operarios por la investigación, se disminuya excesivamente la capacidad de cobertera y no se consigan cumplir las previsiones técnicas en cuanto a la revisión de un número determinado de kilómetros cuadrados de terreno por año.

El personal que trabaja sobre el terreno está distribuido en ocho agrupaciones, cada una de las cuales es dirigida por un geólogo que, dentro de una zona a él asignada por la jefatura, selecciona las áreas a revisar y el tipo de malla a emplear en las mismas, de acuerdo con un conocimiento geológico basado en una cartografía con detalle mínimo del tipo 1:50 000, bien ya existente anteriormente o que él mismo confecciona. En estas zonas, a medida que van siendo cubiertas y estudiadas, se pasa gradualmente desde una labor pura de avance a un trabajo mixto de avance e investigación, pudiendo acabar en los casos de éxito en exclusiva investigación y evaluación de yacimientos.

El personal de técnicas auxiliares se distribuye en seis departamentos, denominados: Sección de Mineralogía, Grupo de Geoquímica, Laboratorio de Fotogeología, Grupo de Geofísica, Laboratorio de Electrónica, Químico y el Grupo de Prospección Aérea, cuya denominación de técnica auxiliar no es correcta dada su misión, que se describe en el próximo capítulo pero que englobamos en el grupo constituído por el 22%, para evitar una excesiva atomización poco expresiva (figura 1).

4. TECNICAS EMPLEADAS Y ANALYSIS CRITICO DE RESULTADOS

Para selección de grandes áreas se emplea la prospección aérea (con una capacidad de hasta 40 000 km^2 anuales, a malla media de 1000 metros), que confecciona mapas a escala 1:50 000 de radiometría corregida por altimetría, con indicación de zonas preferentes, para lo cual se tiene muy en cuenta la geología hasta el punto de que consideramos imprescindible vuelen geólogos, quienes en las indicaciones especifican no sólo las anomalías radiométricas, sino las características geológicas ambientales del terreno en que se encuentran, e incluso tipos de terrenos favorables aunque no hayan detectado anomalías.

Estimamos que la prospección aérea, con sus fundamentales ventajas de rapidez y visión de conjunto, no es resolutiva: ni sirve para eliminar áreas ni, normalmente, sobre todo en sedimentario, detecta directamente el yacimiento: señala zonas de interés preferente sobre las que vale la pena utilizar las otras técnicas terrestres. Indirectamente, e incluso superpuesto al trabajo de Prospección Detallada, hemos utilizado el equipo de Prospección Aérea como apoyo a la cartografía e interpretación geológica, mediante el empleo de la cámara Hasselblad y película en color, lo que, en áreas limitadas y con problemas concretos, es un gran apoyo que da gran agilidad al estudio, sin un encarecimiento notorio; no pensamos, sin embargo, que sea recomendable para generalizarlo a grandes áreas y sin planteamiento previo de problemas precisos.

La Sección de Mineralogía contribuye con sus estudios al conocimiento de la metalogenia de yacimientos. Utiliza, junto a las técnicas comunes para determinación de minerales y rocas, las específicas para radiactivos.

Citaremos solamente, entre las más importantes, microscopía por transparencia y reflexión, densimetría, microquímica, análisis térmico diferencial, porosidad, desequilibrios radiactivos, etc.

La Sección de Geoquímica delimita áreas en Prospección Regional acudiendo al análisis de aguas y aluviones. Para zonas más concretas, se estudian las fracciones arcillosas de suelos, e incluso los contenidos de las cenizas de las plantas. Es muy importante su contribución, ya que considera el uranio directamente y no sus descendientes radiactivos, por lo cual añade directrices orientadoras para investigación de indicios y yacimientos. También se ocupa este grupo de la utilización del método emanométrico. Se está utilizando por primera vez en la zona de Soria; hay un prototipo JEN diseñado por el Dr. De Pedro Herrera y un emanómetro francés. Se encuentran diferencias desde 1 a 3, hasta 30 a 50 emanes. La gran dificultad radica en los problemas derivados de las condiciones climáticas extremadas: lluvia y nieve o sequedad; define anomalías, pero con gran frecuencia el resultado de la determinación es el de simples niveles de porosidad.

La geofísica, enfocada al estudio estructural detallado de los yacimientos, utiliza el método de resistividad con sus diversas variantes de perfiles, rectángulos, sondeos eléctricos, así como el reconocimiento de los sondeos mecánicos, sobre todo en sedimentario, mediante gráficas de radiactividad, resistividad y polarización espontánea.

5. SITUACION ACTUAL DE LA PROSPECCION E INVESTIGACION Y PROGRAMAS PARA EL PROXIMO FUTURO

Resulta obvio que la base fundamental en la planificación del conjunto de medios técnicos y su utilización racional debe basarse sobre tres puntos esenciales: a) los caracteres básicos de los terrenos a prospectar; b) los medios técnicos de que se dispone para este trabajo; c) el objetivo perseguido, que debe ser compatible con la potencialidad uranífera de las distintas formaciones, en cuanto a la existencia de yacimientos actualmente considerados como rentables, y d) la posibilidad de inversión económica para el desarrollo de los programas. No cabe duda que todo ello está en íntima relación con las líneas directrices que marcan la pauta del trabajo, derivada de la propia o ajena experiencia extraída de los trabajos anteriormente efectuados. En el capítulo 2 se ha expuesto ya el proceso evolutivo de nuestra investigación, tal como se ha producido en nuestro caso particular. Se trata ahora de concretar el estado actual de la misma en sus rasgos fundamentales.

Con carácter general podemos decir que en virtud de los factores especificados como puntos básicos a) y c) hemos puesto en marcha un cambio de los objetivos de nuestras investigaciones, dedicando una atención preferente al estudio de las formaciones sedimentarias continentales; por otra parte, ha podido verse que la evolución ha sido gradual, de forma que ya hace unos 10 años se prestaba atención a algunos depósitos continentales, fundamentalmente ligados a capas lignitíferas de nuestro terciario y parcialmente al Triásico Inferior areniscoso.

Los programas de interés central, hasta ahora desarrollados, y que han tenido como base las áreas graníticas y metasedimentarias han

dado, como se dijo anteriormente, las reservas que poseemos, con algunos yacimientos de tonelaje medio y conjuntos importantes. El paso a los actuales programas (fundamentalmente basados en nuestra prospección del sedimentario continental, en nuestras esperanzas de las posibilidades potenciales de estos terrenos, apoyadas por la existencia de numerosas anomalías radiométricas y geoquímicas concretas en áreas de considerable amplitud) ha precisado, por una parte, un cambio de mentalidad y filosofía y, por otra, la puesta a punto de aquellos, que son más específicos para esta investigación. Resulta muy expresivo subrayar, por ejemplo, que mientras una radiometría de superficie, con aparatos de mayor o menor sensibilidad, constituye una tarea básica de la prospección en terrenos cristalinos, y el uso de sondeos correspondía en estas zonas a una fase de exploración profunda y valoración, en nuestras actuales investigaciones de yacimientos sedimentarios, una base primaria de la prospección parte ya de la ejecución de programas de sondeos, dado el carácter no aflorante de los mismos o la relación espacial remota que puede haber entre una anomalía radiométrica superficial y el posible cuerpo mineralizado, cosa no frecuente en los yacimientos filonianos.

Las mismas tareas del geólogo de campo, en la consideración de los «factores guía» significativos, o imprescindibles de hacer constar en la cartografía, el conocimiento de la evolución del ambiente geológico, de la litología, de la tectónica, de la profundidad del nivel freático, etc., suponen una nueva orientación de su misión profesional. Los detalles geológicos complementarios de la radiometría en la prospección aérea tienen en este caso, una orientación diferente, por ejemplo, observación de colores, de alteración, del aspecto de las cuencas, de las diferencias de facies visibles, etc.

Todas estas circunstancias condicionantes de nuestras actuales tareas de prospección en terrenos sedimentarios no han supuesto por nuestra parte el rechazo de lo hecho anteriormente en sucesivos programas, sino una consecuencia del gran interés que ya teníamos por el conocimiento indirecto de los yacimientos uraníferos en rocas arenosas de otros países, aumentado por nuestra observación directa de los yacimientos de EE.UU y los amplios y fructíferos cambios de impresiones que hemos tenido con nuestros colegas americanos, en ambos países. Todo ello, ligado a la nueva mentalidad que ha tenido lugar, a escala mundial, sobre las dimensiones y otros parámetros que actualmente se exigen a las condiciones de explotabilidad aceptables en el contexto general de la economía del uso pacífico de la energía nuclear y sus repercusiones en el mercado actual, son caracteres en nada parecidos a los de hace muy pocos años, como ya se indicaba en la introducción de este trabajo.

Por nuestras condiciones especiales debemos seguir la prospección de áreas de terrenos paleozoicos, en los que, como ya ha sucedido en etapas anteriores, hemos podido localizar yacimientos de tonelaje interesante por sí mismo, o bien conjuntos o enjambres de zonas enriquecidas cuya proximidad podría darnos tonelajes, con las condiciones económicas exigidas.

De todo lo dicho se desprende que nuestra cuidada preparación de los programas actuales y futuros se viene realizando de una forma gradual, sistemática, razonada, que permite mejor la adecuación de nuestro trabajo.

Como resumen, puede exponerse nuestro programa actual de trabajo mediante la diferenciación de dos áreas en la península: la parte occidental de la Meseta, desde la falla del Guadalquivir hasta Galicia incluida, constituida esencialmente por afloramientos graníticos y metasedimentos paleozoicos, sobre los que se ha investigado a fondo con el hallazgo de las agrupaciones de yacimientos de las zonas de Andújar, Don Benito, Cáceres y Ciudad Rodrigo; y el resto del país, de carácter sedimentario, postpaleozoico, en el que se integran grandes extensiones de terrenos originados en régimen continental, como son los triásicos, infracretácicos y determinadas facies eocenas, oligocenas y miocenas, en los que son notorias sus buenas características favorables para contener yacimientos uraníferos.

En la primera de las dos grandes áreas antes delimitadas, quedan por revisar terrenos e investigar indicios en las provincias de Orense-Zamora, Avila-Segovia-Toledo, Cáceres-Badajoz y Sevilla (cuenca del Viar y terrenos circundantes). Se ha de comenzar además la revisión de numerosos indicios últimamente localizados por la prospección aérea en la provincia de Ciudad Real.

En la segunda área, mucho más extensa que la anterior, aún descontando buena parte de terreno con perspectivas poco favorables, queda una gran tarea por realizar, en parte por su gran superficie y también por haberse acometido su estudio más recientemente.

Dentro de ella, consideramos como áreas preferentes la cobertera sedimentaria de la Meseta, incluyendo sus bordes, sobre todo el NE (Cordillera Ibérica).

Habremos de enfrentarnos posteriormente, ateniéndonos a las posibilidades existentes de personal, con el sector oriental de la Cordillera Cantábrica, la Pirenaica, la Costero-Catalana y parte de las Béticas, además de los bordes de la depresión del Ebro.

En las últimas existen posibilidades teóricas y en algún caso reales, pero su tectónica más violenta o topografía difícil hacen más problemáticos los resultados y su prospección sistemática. Sin duda alguna, habrán de revisarse estas áreas en el futuro, después de haberlo sido las preferentes. Algunos núcleos, ya localizados y con perspectivas, indican la conveniencia de investigarlos a lo largo del III Plan Cuatrienal.

Es ya importante el área cubierta con la prospección aérea desde el año 1967, en que se comenzó a utilizar: 109 500 km^2. En 1971 se han revisado otros 35 000 km^2 que, sumados a los anteriores, totalizan casi 145 000 km^2. Con ello se ha conseguido sobrevolar buena parte de las áreas preferentes.

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SOME ASPECTS CONCERNING THE FEASIBILITY OF RADIOMETRIC METHODS FOR URANIUM EXPLORATION IN FINLAND

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Abstract

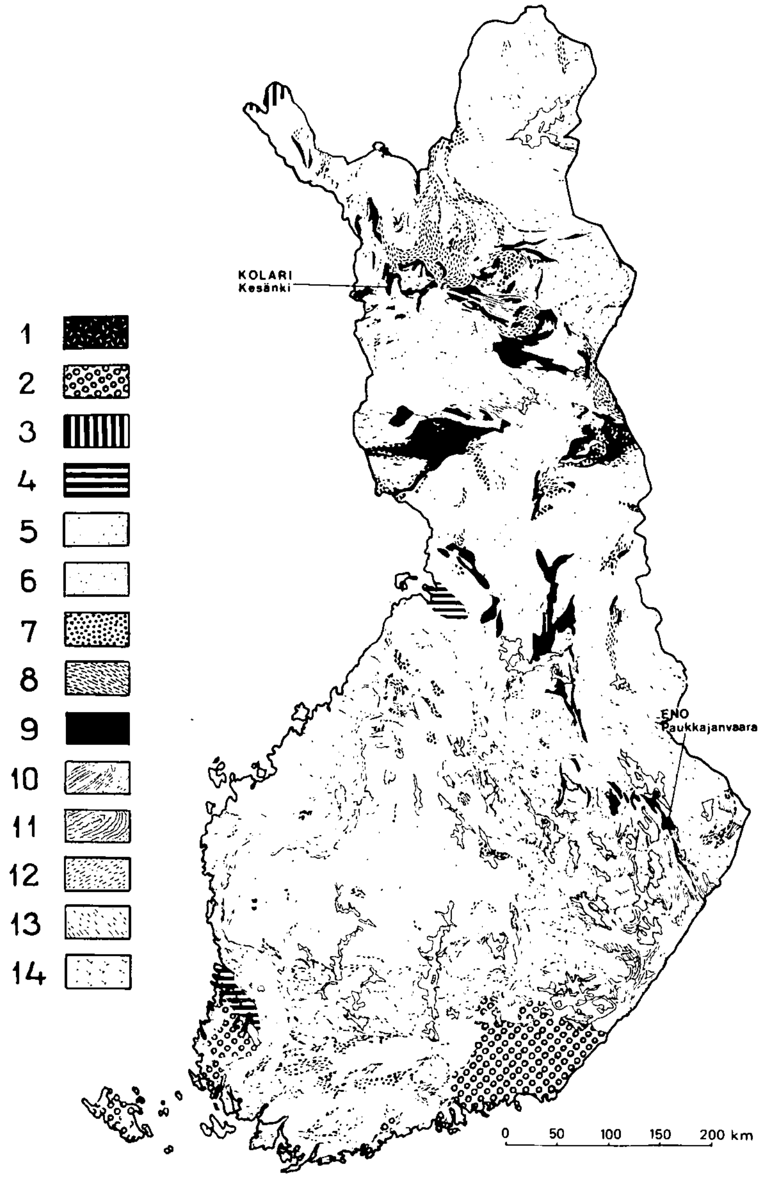
SOME ASPECTS CONCERNING THE FEASIBILITY OF RADIOMETRIC METHODS FOR URANIUM EXPLORATION IN FINLAND.

The feasibility of the survey methods employed for uranium exploration is restricted by Finland's geographical location, as well as by its vegetation, waterways and soil. Systematic exploration for uranium has been carried out on a rather small scale, and has been concentrated mainly on extensive quartzite areas. The search for boulders, a method in which the boulders loosened from the bed rock by glacier ice or frost are traced and used for the localization of the outcropping mineralization, has shown its validity both in ore and uranium exploration. This paper evaluates the feasibility of employing ground and airborne radiometric methods as well as radon determinations. The results obtained by ground methods are reported in the light of the Kesänki case-history.

1. INTRODUCTION

Limits are placed on the use of radiometric methods for uranium exploration in Finland by the geographical location of the country, its vegetation, waterways and soil. Great seasonal changes are characteristic of the Finnish climate. In winter, the entire country is covered with snow, but there is no perma-frost. About 10% of Finland's surface area consists of lakes, the number of which has been estimated to be about 55000. In the so-called lakeland of Finland, i.e. the central part of the country, lakes cover 25% of the surface area. The lakes freeze in winter and the geophysical measurements can be done on ice. Almost all of Finland belongs to an extensive coniferous zone marked by dense forests. With the exception of the northernmost parts of the country, where there are relative variations in elevation from 300-500 m, the terrain is for the most part flat.

The soil covering the bedrock was formed towards the end of and after the close of the Ice Age. Most of it is a result, either directly or indirectly, of the activity of glaciers. Since the Ice Age, a part of the bedrock has turned into soil. Those rocks which are least resistant to weathering have sometimes disintegrated into gravel. Particularly in northern Finland, the cold weather has caused the rocks on the fells to break up into extensive regions of rubble. The bedrock scoured by the continental ice sheet is now covered by a layer of overburden, the thickness of which varies from 0-100 m, with an average thickness of 8.5 m. Also typical of the Finnish terrain is the extensive coverage of swampland, which accounts for about one-third of the surface. The areal distribution of exposures,. which hardly make up more than 5% of the surface, is uneven. There are some areas, e.g. in the archipelago, where exposures occur abundantly, and other



1. OLIVINE DIABASE
2. GRANITE, MAINLY RAPAKIVI (PRE-CAMBRIAN)
3. PALEOZOIC SCHISTS (CALEDONIAN)
4. UNMETAMORPHOSED SCHIST (JOTNIAN)
5. GRANITE AND ACID PLUTONIC ROCKS IN GENERAL
6. QUARTZ DIORITE AND GRANODIORITE
7. GABBRO, ANORTOSITE AND ULTRABASIC ROCKS
8. METABASALT, AMPHIBOLITE AND HORNBLENDE GNEISS
9. QUARTZITE
10. PHYLLITE AND MICA SCHIST
11. MICA GNEISS MIGMATITE
12. LEPTITE
13. GRANULITE
14. GRANITE GNEISS

FIG. 1. Pre-quarterly rocks of Finland, based on the geological map by A. Simonen, 1959.

areas where only occasional small exposures might be encountered per 100 km^2. The abundance of swamps and lakes as well as the overburden hinder the use of radiometric measurements. The dense forests make it impossible to use the heavier types of measuring equipment installed in vehicles, except where there is a network of roads.

The Finnish Precambrian bedrock is composed, for the most part, of crystalline rocks, particularly gneisses and granites (Fig. 1). Uniform schist zones occur in the bedrock with areas of plutonic rocks between them. The schist zones are composed of metamorphic rocks which were originally sediments such as sand, clay and the products of volcanism. The plutonic rocks are mostly granodiorites and granites. Uranium exploration has been carried out on a small scale in Finland and little information is available as to the areal distribution of uranium. On the other hand, there is considerable exploration for sulphides and iron ores throughout the whole country. Uranium exploration is now mainly done by the state-owned Outo-kumpu Oy mining company and the Geological Survey, and is almost entirely limited to the quartzite areas marked in black on the geological map. Investigations have led to the discovery of several uranium mineralizations and to detailed field studies accompanied by diamond core drilling. However, further investigations have usually shown that the deposits are not economically profitable. The only uranium mine in Finland, which was in operation during the years 1960-1961, was also located in a quartzite area in Eno.

2. GROUND MEASUREMENTS

Uranium exploration got under way in Finland in the 1950s. From the start, the exploration has been based on the search for boulders and the radioactive survey of exposures. In the 1950s, Geiger counters were employed, but in the 1960s these were replaced by scintillometers. The so-called search for boulders has proved to be a very effective method both in ore and uranium exploration. It entails tracing the boulders broken off from the bedrock by glaciers or frost and making use of them to pinpoint the outcrop of an ore deposit. With the aid of reconnaissance and systematic radiometric measurements done on the ground, it has been possible to localize abundant "radiating" uranium boulder trains in the vicinity of mineralizations in quartzite areas, whose outcrop was covered by overburden. The size of the boulder in these trains may vary from a few cubic centimetres to several cubic metres and there are sometimes hundreds of boulders in one train. To localize the source of the boulders or radioactive anomaly, systematic radiometric mapping, radon measurements or geological detail mapping are employed. Scintillometric measurements are carried out systematically on the ground both summer and winter. In the winter, the gamma radiation is measured from the lowest layer of snow next to the surface of the earth, since the radon gas emanating from the earth will have collected in this layer. The method is well suited to the parts of Finland with the stony terrain in which radon measurements are difficult to do. The anomalies found by scintillometer are to be checked by spectrometer. The emanometers discussed by Wennervirta and Kauranen [1] are employed, for example, for the radon measurements in the overburden. With these instruments, the gamma activity is determined from the active

carbon through which the air has been sucked from the soil. Radon determinations from water samples are also carried out by emanometers. In these the radon content is determined directly from the alpha activity of the sucked-in gas.

3. AERO MEASUREMENTS

Very positive results have not been obtained in Finland concerning the suitability of aeroradiometric methods for uranium exploration. It is true, though, that the equipment has been very modest. In the airborne measurements, the total volume of the crystal detectors used for recording the radiation has been small, about 100 in^3. There has been no decisive benefit from the results of airborne surveys in the localizing of uranium mineralizations, which are frequently point-like radiation sources, although in some experiments the measurements were carried out from a helicopter flying at a low altitude and at a reduced speed.

Recent developments in aerospectrometry mean that low-altitude flights have had to be reconsidered. Since previous experience has given rather negative results as to the feasibility of these flights, Outokumpu Oy ordered a test flight for the summer of 1972 by the firm of Prakla-Seismos (Federal Republic of Germany), the aim of which was to investigate whether the aerospectrometrical equipment now available would be of any practical use under Finnish conditions (Fig. 2). The test flight was carried out by helicopter over two areas, both of which are well-known geologically. The specifications for the test flight were strict: an altitude of 50 m, a distance between lines of 125 m, and a crystal volume of 1000 in^3. The measurements had to be done by helicopter to ensure that a sufficiently low flying speed, 100 km/h, and altitude are maintained, since the variations in elevation are rather large in one of the investigation areas. The digital recording data was processed by computer. In the course of the flight the radiation on the U, Th, K channels and the total radiation were recorded.

1. Gamma-ray spectrometric survey
2. Crystal volume 1000 in^3 plus 300 in^3 for atmospheric ^{214}Bi
3. Flight altitude: 50 m
4. Flight speed: 100 km/h
5. Line separation: 125 m
6. Digital and analogue recording of five channels:
   total count
   potassium (^{40}K)
   uranium (^{214}Bi)
   thorium (^{208}Tl)
   atmospheric ^{214}Bi
7. Digital and analogue recording of altitude
8. Registrations at 0.3-s intervals
9. Computer data processing with altitude and compton-scatter correction to isoradiation contour maps of different channels and ratios
10. Ratios: U/K, U/Th and Th/K
11. Contractor: PRAKLA-SEISMOS, Hannover, Fed. Rep. Germany

FIG. 2. Flight specifications of a helicopter test survey in Finland in summer 1972.

Also the atmospheric ^{214}Bi was recorded by an experiment. The use of a large crystal volume made it possible to make calculations for so-called ratio maps on the basis of statistically reliable data. In spite of the high demands set concerning the quality of the test flight, information obtained from it, at the very best, comes from a considerably more limited area than that obtained from, for example, magnetic and electromagnetic airborne measurements. In Finland, the latter give useful results directly from the bedrock even in areas which are covered by lakes, swamps and overburden. It would seem that the potential of aerospectrometry is as limited as that of geological mapping, in which information is only obtained from exposures and from beneath thin layers of overburden. The aims of the test flight were to investigate whether it is possible to find radioactive boulder clusters by airborne measurements and whether the overburden is capable of reflecting the radioactive properties of the bedrock beneath it with sufficient accuracy. The Geological Survey also intends to start low-level aerospectrometric investigations in the near future.

4. KOLARI, KESÄNKI AREA

In the following case history, radiometric ground survey results from the Kesänki area are briefly reported. The geological formation, which was the object of the study, is composed of metamorphosed sedimentary rocks of different types with arkose, sericite and orthoquartzites as the main components. A systematic reconnaissance scintillometric survey was done in the area, on the basis of which the profile map depicted in Fig. 3 was made. For the profile output, the continuous weighted average of three sequential points was calculated. The reconnaissance survey was made with a 500-m line separation and a 20-m spacing between the survey points. The measuring team usually consisted of three persons, one observer and two boulder searchers. The latter walk along both sides of the survey profile and look for boulders with a scintillometer recording their locations. An extensive cluster of boulders was discovered at the strong anomaly on profile x 7504. 00, which is probably the main cause of the anomaly. For experimental reasons, an aerospectrometric survey was done on the profile, the results of which are compared with the curve obtained by the reconnaissance ground measurements in Fig. 4. The results of the aero-survey flown by the firm Rautaruukki Oy indicate a clear correlation between the uranium and total channels and the anomaly obtained by ground measurements. The aero-experiment with a flight altitude of 30 m and a 6 × 5-in. crystal supports the view that radioactive cluster of boulders can also be detected by aero-survey under favourable conditions.

In the Kittilä area, where there are numerous high hills, a radon study was performed from water samples collected from streams, lakes, rivers and springs in the area. The results depicted as black colums on the map in Fig. 5 indicate a fairly large variation. In the environment of a scintillometric anomaly detected on the Kesänki fell, which is marked by a circle in Fig. 5, radon abundances are encountered which somewhat exceed the background values. The highest concentrations occur in the centre of the map in an area which, so far, has not been subjected to a closer study and in which there are several quartzite hills. The anomaly and its

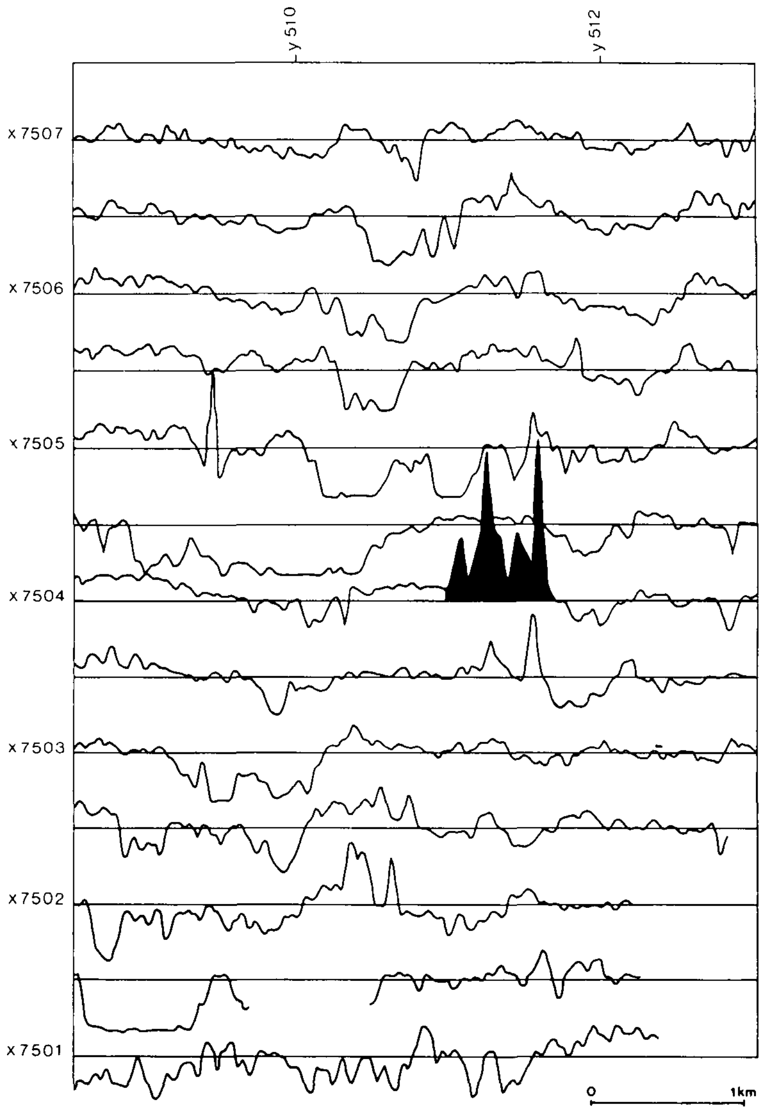


FIG. 3. Reconnaissance scintillometer survey of the Kolari, Kesänki area.

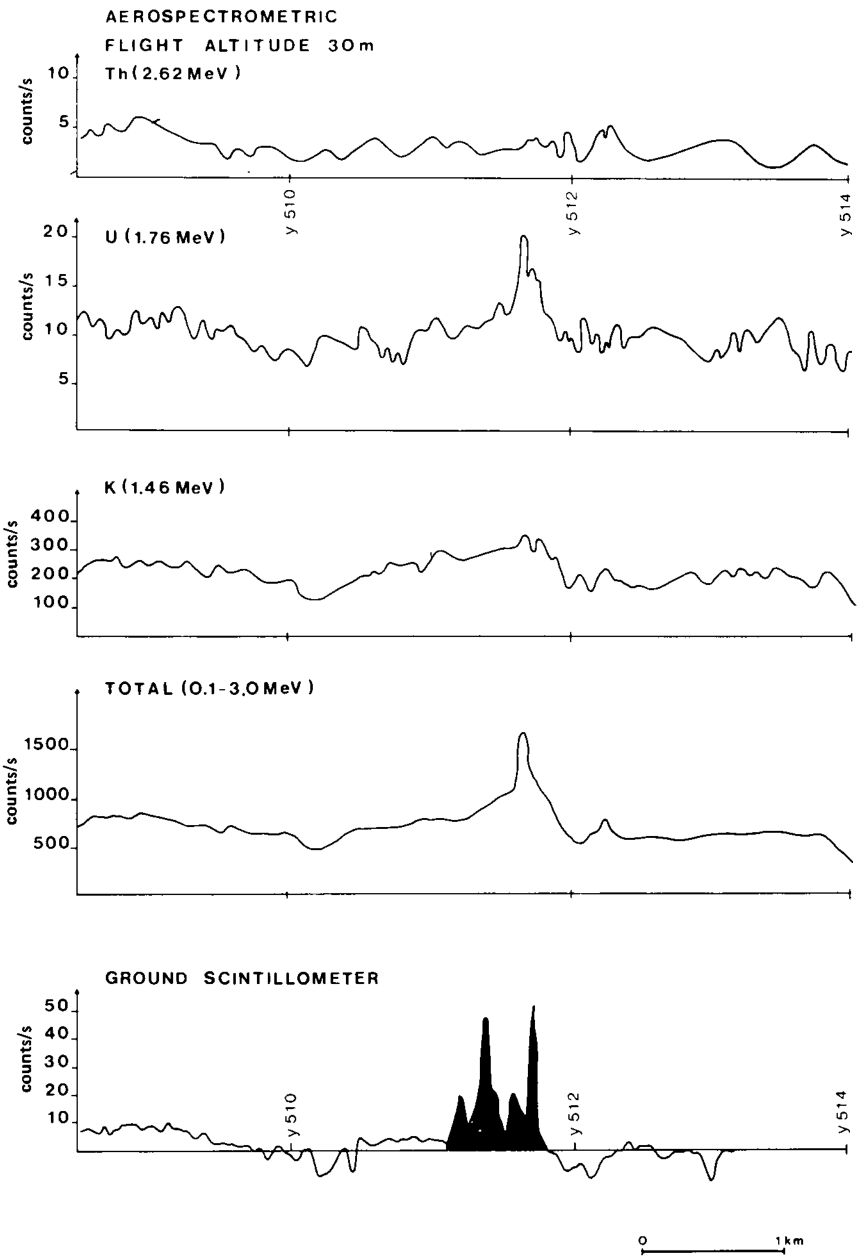


FIG. 4. Aerospectrometric survey compared with ground scintillometer survey of the Kesänki area of profile x 7504. 0.

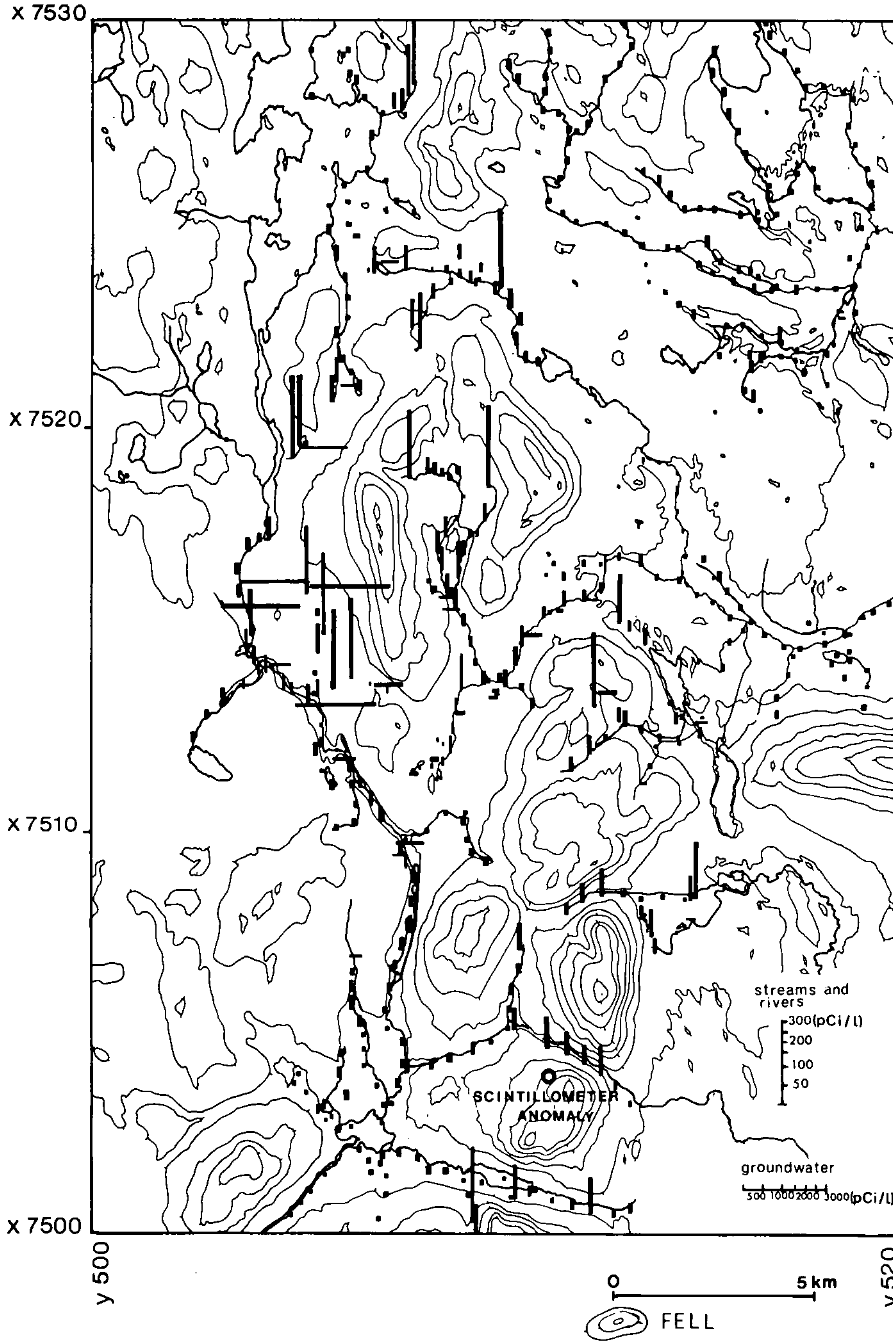


FIG. 5. Radon content of waters in the Kittilä area.

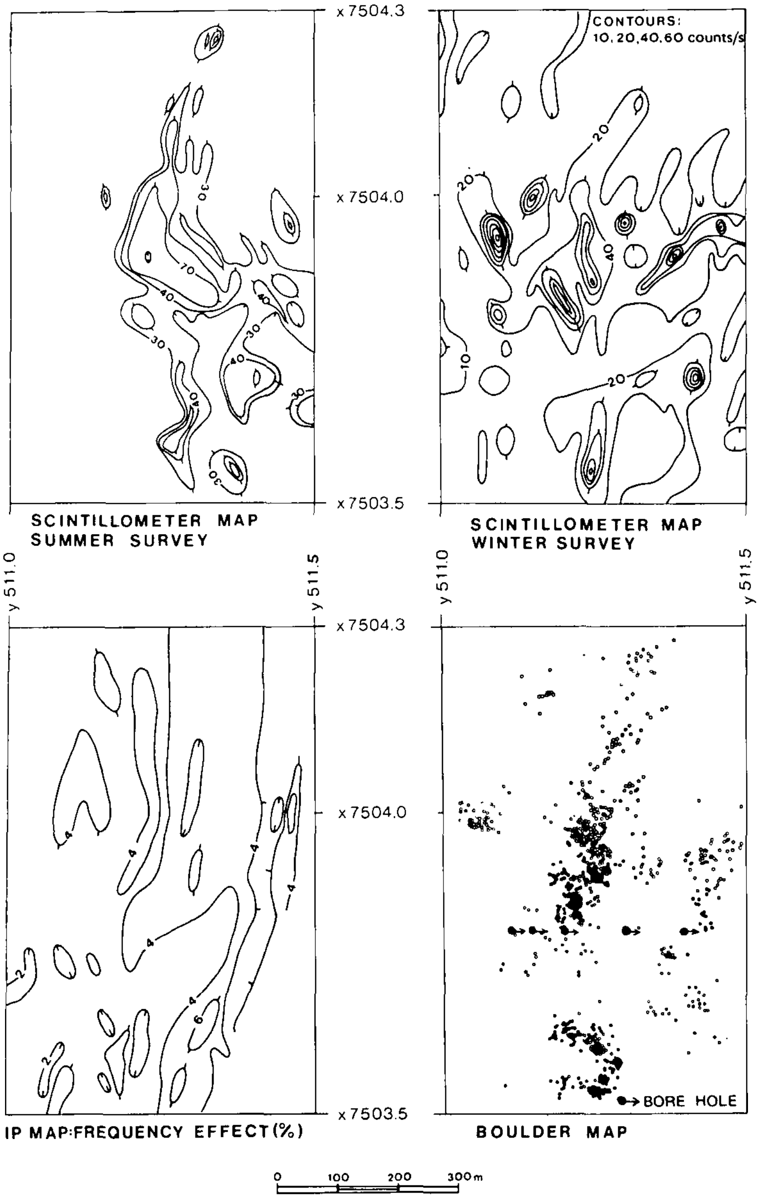


FIG. 6. Comparative summer and winter scintillometer ground survey of the Kolari, Kesänki area.

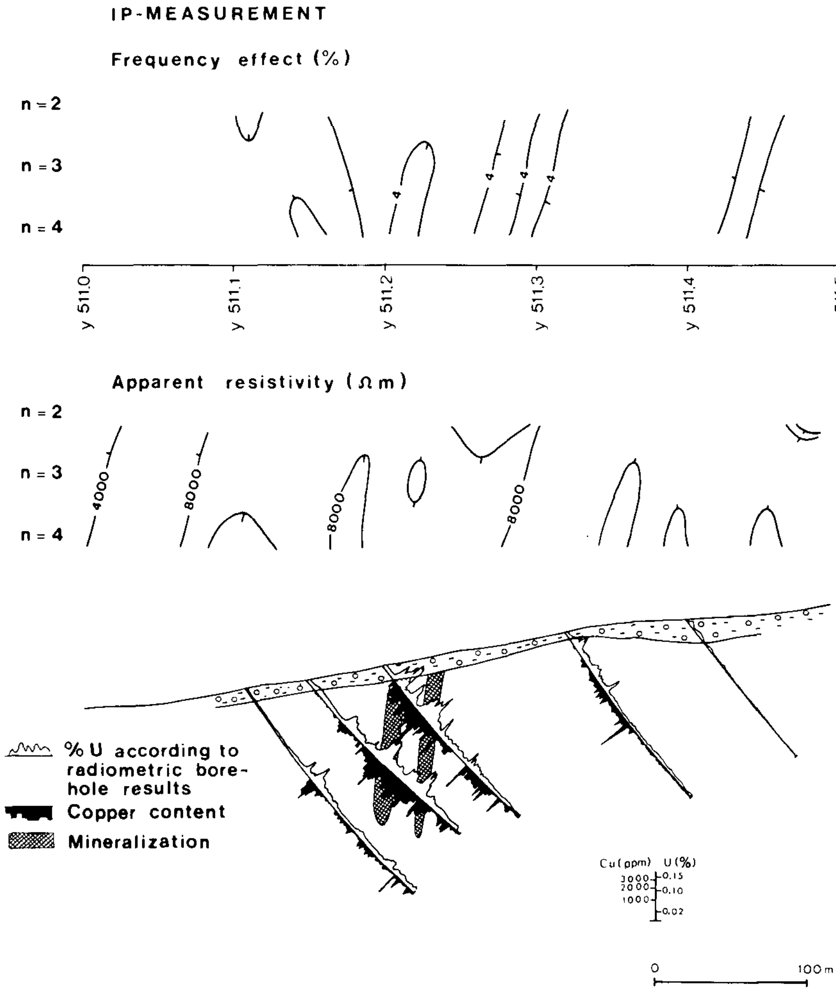


FIG. 7. Comparative IP measurements in the Kolari, Kesänki area of profile x = 7503. 80.

surroundings discovered by the reconnaissance survey were also studied in detail with a scintillometer both in summer and winter by employing a 50-m separation between the profiles and a 10-m spacing between the survey points (Fig. 6). In summer the scintillometer was kept 0. 5 m above the ground while doing the observations. Comparison of the boulder map, on which the uranium-bearing boulders found in the survey area are marked, with the scintillometric maps, shows that a correlation exists between the boulder clusters and the radiometric anomalies. The scintillometric maps were drawn on the basis of the values obtained by computing the weighted averages of the three sequential survey points in each profile.

Supplementary studies showed that the boulders were very local. Preliminary drilling revealed a uranium mineralization in a sericite-

quartzite formation close to the boulders. Afterwards it was established by diamond core drilling that the abundance of uranium corresponded well with the average abundance in the boulders. Apart from uraninite, the quartzites contain small amounts of chalcopyrite and pyrite. The clear regional correlation between uranium and copper made it possible to employ IP measurements in the investigations. Figure 6 shows a frequency effect map which was obtained by the variable frequency method. The survey was done by a dipole-dipole configuration with a spacing of 20 m between the electrodes. The anomalies shown on the map are weak 4-6%. However, in profile x 7503.80 for example, the frequency effect anomaly is almost directly above the exposure of the mineralization (Fig. 7). A radiometric total-count measurement was done in the bore-holes, the results of which are marked along the drill hole together with the copper abundances obtained from the drill core. The highest copper abundances coincide with the uranium mineralization. However, the conductivity of the mineralization is so low that it is not indicated by the results of the apparent resistivity measurements.

5. CONCLUSION

The experience gathered so far seems to indicate that a scintillometric survey carried out with a rather large distance between profiles and supplemented with spectrometric measurements in the anomalous areas is well suited as a regional method for use in conjunction with stream sediment studies and radon measurements done from water. Under Finnish conditions these methods supplement each other successfully. Thus, it might be feasible to restrict ground survey merely to those areas which are considered favourable on the basis of airborne measurements. In addition to the radon measurements, plans have been made for commencing uranium determinations from water. Scintillometric and spectrometric surveys as well as radon measurements on soil seem quite well suited to systematic detailed studies in summer and winter. In some cases it has been difficult to interpret the radiometric anomalies produced by soil because the glacial ice transported soil from its original site.

REFERENCES

[1] WENNERVIRTA, H., KAURANEN, P., Radon measurement in uranium prospecting, Extrait des Comptes Rendus de la Société géologique de Finlande, No. XXXII (1960).

DISCUSSION

S. H. U. BOWIE (Chairman): Thank you Mr. Ketola for your most interesting paper on the practical results of your work in Finland, a country that is extremely difficult to prospect in, because as you rightly say, you have difficulties from snow cover, lakes, swamps, glacial drift and also from large areas of densely forested country. This makes the task of locating uranium an extremely difficult one, and I am interested myself in your approach and also perhaps in comparing your approach

with our own in the northern part of the British Isles, where we have some of the difficulties that you have – not quite all of them, but certainly a lot of glacial and peat cover. I am sure that most people here are very grateful to you for introducing this paper.

J. CAMERON: I was very interested in your summer and winter radiometric results. If they do refer to the same area, they seem to be markedly different. Could you tell us the reasons for this.

M. KETOLA: Yes, there are considerable differences in those maps. We have not got much experience about the winter measurements by scintillometer. In some cases we have observed that more anomalies are obtained in winter than in summer. One reason for this might be the fact that in winter the detector of the scintillometer is carried closer to the ground surface than in summer. We push the detector through the snow into the lowest part of the snow layer, since the radon gas emanating from the earth is collected in this layer, as mentioned in my paper. In summer we usually perform measurements at an altitude of 0.5 m above the surface or even somewhat higher. For instance in Kesänki area there are a lot of boulders, which produce most of the scintillometer anomalies. In summer measurements carried out on a higher level, we perhaps lose some boulder anomalies.

D. OSTLE: I wonder whether anybody has carried out radon determination in snow, because there would appear to be the possibility of a "damming" effect on the radon, possibly augmented by high barometric pressure. If there is a blanketing effect by the snow involving a build-up of radon in the bottom layers, there would presumably be deposition of ^{214}Bi in the lower parts of the snow layer and this might result in a gamma anomaly.

A. G. DARNLEY: We observed last winter that snow appears to result in build-up of mercury in the bottom layers of snow over mercury occurrences. Copper and zinc also appear to be trapped in the bottom layers of snow in the vicinity of anomalies, so I think one would expect the same to extend to ^{214}Bi and radon.

H. FAUTH: I also estimated several elements in snow, such as mercury and copper and zinc. We found anomalies and also we found that these anomalies can come from far away with the wind, and so possibly in the snow there are also radioactive substances which are coming from other places.

L. LØVBORG: I have noticed in Greenland that fresh snow may have a very high alpha radioactivity which must be ascribed to radon.

J. F. DAVIS: You mentioned the collection of atmospheric ^{214}Bi – I was wondering if you found any significant differences between that and that which you attributed to coming directly from the ground. In other words, do you have an effect of radon clouds affecting the survey?

M. KETOLA: I mentioned in my paper that the atmospheric ^{214}Bi will be recorded only experimentally. We are going to investigate if there is atmospheric ^{214}Bi at the 50-m level affecting the results of the survey.

H. H. ADLER: I do not know whether I understood your paper to indicate that you had met radon in water analyses – is that correct? If these measurements were absolute, what sort of values were you obtaining in terms of pico curies per litre?

M. KETOLA: Our instrument is calibrated in such a way that the results in Fig. 5 are about the same as absolute values in terms of pico curies per litre.

H. FAUTH: I think it is very difficult to estimate radon in water. I had several experiences and I now estimate uranium content of the water because the radon content of the water gives different results.

D. OSTLE: Would Mr. Ketola kindly tell us what are the average, or the maximum/minimum lengths of the dispersion trains from uranium deposits in glacial material – an order of magnitude would be useful.

M. KETOLA: This is a difficult question – the boulder trains can be very dense and local on the fells in northern Finland, where the boulders were broken off from bedrock by frost. The length of the trains vary from some hundred meters to one kilometer as you can see in Fig. 6. In Finland there are also very long boulder trains broken off from bedrock by glaciers with a small number of boulders. The length of such trains may reach several kilometers. It is very difficult to give an exact number.

S. H. U. BOWIE: Generally speaking you would say that it is not more than a few kilometers – would that be correct?

M. KETOLA: Yes – we seldom can trace them for several kilometers. There may be many trains in the same area and if we find a boulder it is impossible to say to which train it belongs.

EXPLORATION OF URANIUM DEPOSITS IN TERTIARY CONGLOMERATES AND SANDSTONES IN JAPAN

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Abstract

EXPLORATION OF URANIUM DEPOSITS IN TERTIARY CONGLOMERATES AND SANDSTONES IN JAPAN.

In Japan there are two uranium mines, the Ningyo-toge mine and the Tono mine, which occur as penecordant uranium concentrations in the basal part of Neogene formations immediately overlying a Mesozoic granitic basement. The uranium concentrations occur in the depressions of the granite surface which are considered to be former river channels. These deposits were discovered as a result of an extensive carborne radiometric survey designed to cover the entire country; subsequent exploration employed various methods. Detailed mapping coupled with geophysical methods provided data on the extent of the ore-bearing horizons and the topography of the basement surface. Drilling was carried out quite extensively. A large-size-diameter mud fluid method was applied to produce maximum core recovery and succeeded in obtaining perfect core samples even in loose sedimentary rock. Exploratory tunnelling proved the final dimensions and the grade of the ores. On the other hand, basic studies of the geochemistry and mineralogy of the ores, and of the petrology of the granitic rocks which are considered to be the source of the uranium, proved invaluable for exploration, since they yielded detailed understanding of the nature of the deposit and the ores. A case history of the exploratory work of one of these deposits, which is essentially a combination of more or less orthodox methods, is presented, together with discussion of the various phases of the project.

1. INTRODUCTION

Uranium occurrences other than those in pegmatites were unknown in Japan until 1954 when the Geological Survey of Japan (GSJ) began nationwide systematic uranium exploration. Atomic Fuel Corporation, a Government corporation established in 1956, undertook detailed survey of the areas discovered by the GSJ to have radioactive anomalies. The Atomic Fuel Corporation was absorbed into the newly founded Power Reactor and Nuclear Fuel Development Corporation (PNC), a quasi-government organization, in 1967.

The GSJ and PNC have found more than one hundred localities with positive radioactive anomalies (Fig. 1). The geologic environment of Japan, however, is not favourable for the concentration of uranium and most of these anomalies were not of economic value. At present, ore reserves of approximately 8 000 metric tons of U_3O_8 with a production cost of less than $15/lb are confirmed. Ningyo-toge and Tono deposits are the representative uranium deposits, and the reserves of the two constitute more than 90% of the domestic uranium reserves to date.

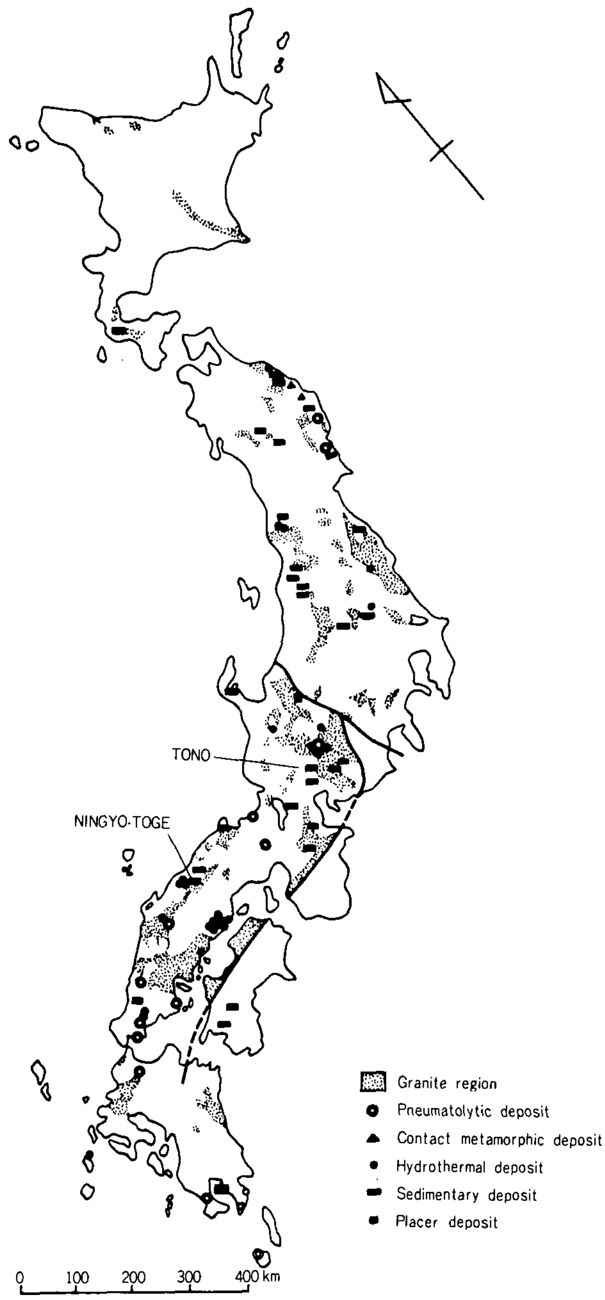

FIG. 1. Distribution of major radioactive anomalies in Japan.

During the course of this exploratory work, many methods were applied with varying degrees of effectiveness. The following is an attempt to introduce briefly and evaluate the methods applied as a case history of exploration of sandstone-type uranium deposits.

2. AIRBORNE RADIOMETRIC SURVEY

During the earlier phases of uranium exploration in Japan airborne radiometric survey was used as a means of efficiently delineating promising areas. It was first tested in 1955, and during the period 1956 - 1960 a total of 61 000 km^2 was flown with traverse intervals of 1.5 - 2 km at altitudes of 200 - 300 m and speed of 180 - 200 km/h. The measured radioactivity was calibrated to values corresponding to 200 m in ground-to-aircraft distance [1]. The result, however, was somewhat disappointing as it showed a marked difference between geological units such as granitic rocks and sedimentary formations while failing to indicate areas or outcrops of high radioactive anomalies. Many factors contributed to this, such as the very complex nature of the geology, small-sized individual units and the very complicated topography (Fig. 2).

Thus the method is considered unsuited to Japan and has not been used since. It should be emphasized, however, that airborne survey is indeed one of the most effective methods of prospecting in areas with less complicated topography and also where the individual geological units are large enough to permit stable natural counts for some distance. The recent discovery of large deposits, for example the Nabarlek deposit in Australia, clearly demonstrates the effectiveness of the method. Also, recent developments in instrumentation and equipment have made this method most useful especially for delineating areas for detailed ground survey.

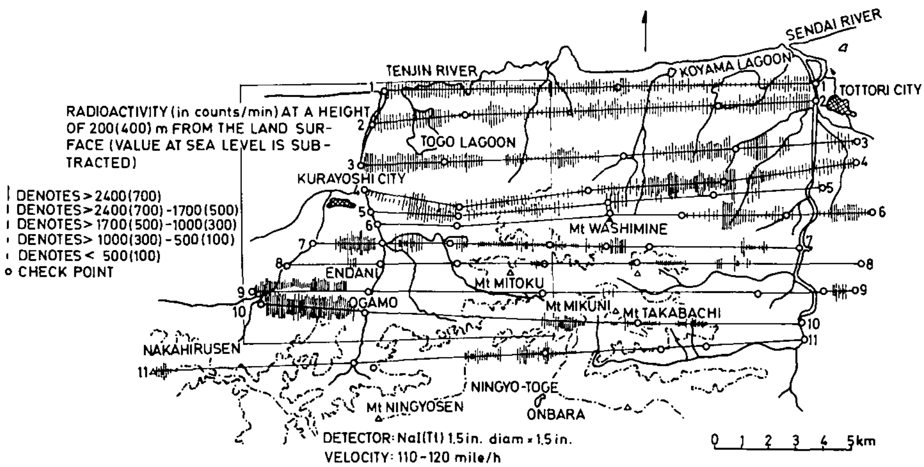

FIG.2. Airborne radiometric survey results in the Ningyo-toge area. Zones of high radioactivity are the granitic areas.

3. CARBORNE RADIOMETRIC SURVEY

The most efficient areal radiometric survey in Japan is the carborne method. In fact all of the important anomalies were discovered by carborne survey teams. The effectiveness of this method in Japan is primarily because the country is densely populated and thus the road network is very closely spaced allowing the use of vehicles for fairly detailed work.

The speed of the vehicles is 20 - 30 km/h during the survey. The detector consists of two NaI crystals, the size of which was 1.5×1.5 in. during the earlier investigations, while those in current use are 3.0×5.0 in.

The carborne survey teams covered approximately 200 000 km^2 in Japan and have discovered about 100 anomalies. This method is the most effective method for reconnaissance survey in areas where it is possible for vehicles to make closely spaced traverses [2] (see Fig. 3).

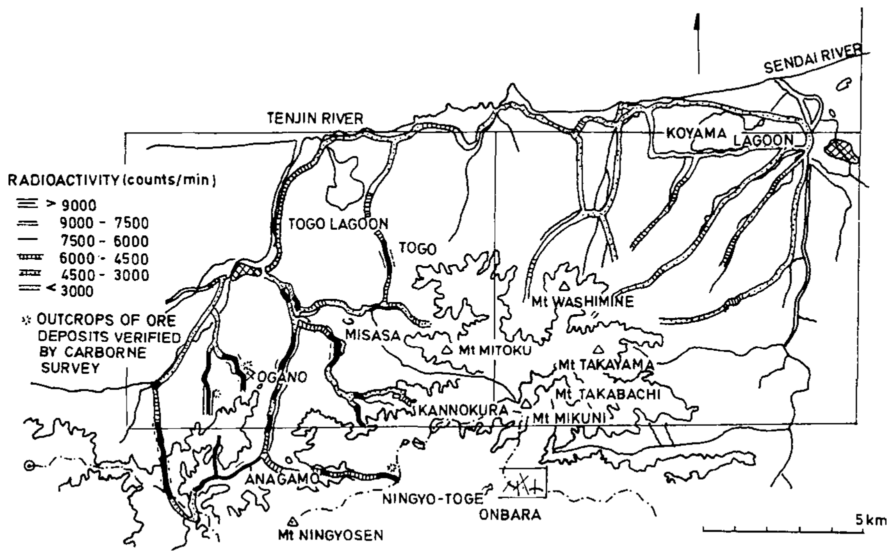

FIG. 3. Carborne radiometric survey results in the Ningyo-toge area.

4. SURFACE RADIATION SURVEY

When the radioactive anomalies discovered by various methods are found to be on a small scale and in areas of igneous rocks, the possibility is that they are not worth further work. If on the other hand the anomalies are in sedimentary formations, the small size at the outcrop does not necessarily indicate lack of continuity. In such cases, the usual method is to dig trenches across the anomalies and to clarify the relationship between the anomalies and the geological succession. For these detailed surveys,

hand-held gamma-ray detectors are indispensable. And for cases where it seems promising, continuity of the anomalies and of the horizon must be investigated.

5. GEOCHEMICAL PROSPECTING

Sandstone-type uranium deposits are commonly buried and do not exhibit surface radioactive anomalies. As the uranyl ion is quite soluble in groundwater, however, the uranium content of waters near the deposits are considerably higher than those passing through barren areas [3].

Thus geochemical prospecting by utilizing the uranium content of groundwater was proven to be useful in various localities, and in the Tono district drilling is now being done on the basis of the results of geochemical prospecting. This method is especially effective in locating blind ore bodies in areas where mineralization is known to have occurred.

6. DETAILED GEOLOGICAL SURVEY

Detailed geological investigation was carried out in the vicinity of the Ningyo-toge deposit, which was the first significant discovery in Japan. It was subsequently established through such work as trenching, drilling, and tunnelling, that:

(a) Uranium mineralization occurred at the basal part of the Tertiary formations which were deposited on the depressions of basement granitic rocks. The depressions were paleostream "channels" in some places and wider "basins" in other parts.
(b) Mineralization occurred after the deposition of the host rocks.
(c) Uranium-bearing beds were non-marine sandstones or conglomerates.
(d) Basement rocks underlying the Tertiary uranium-bearing beds were always granitic rocks.

Understanding these geological characteristics is most important for prospecting. In the case of our sandstone-type deposits, the search for the depressions of the surface of the basement granitic rocks became the first phase of operation (see Figs 4 and 5).

7. GEOPHYSICAL PROSPECTING

Aside from radiometric survey and logging, geophysical methods have not been used for locating sandstone-type uranium deposits as in the cases of other metallic minerals. But these methods have proven to be quite useful, under favourable conditions, for the determination of the thicknesses of the sedimentary formations overlying the basement granite (Fig. 6). Seismic, gravity and electrical methods were tried in order to evaluate the methods for this work. The seismic and electrical methods were not quite successful in the Ningyo-toge area where the surface topography was very rugged. For example, the seismic method showed only the general

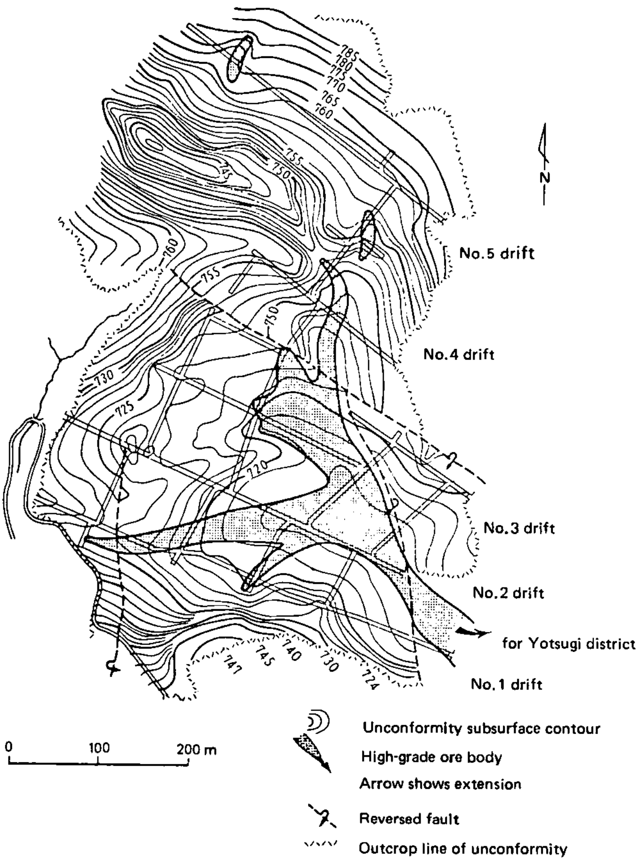

FIG.4. Typical channel-type ore bodies in the Ningyo-toge area.

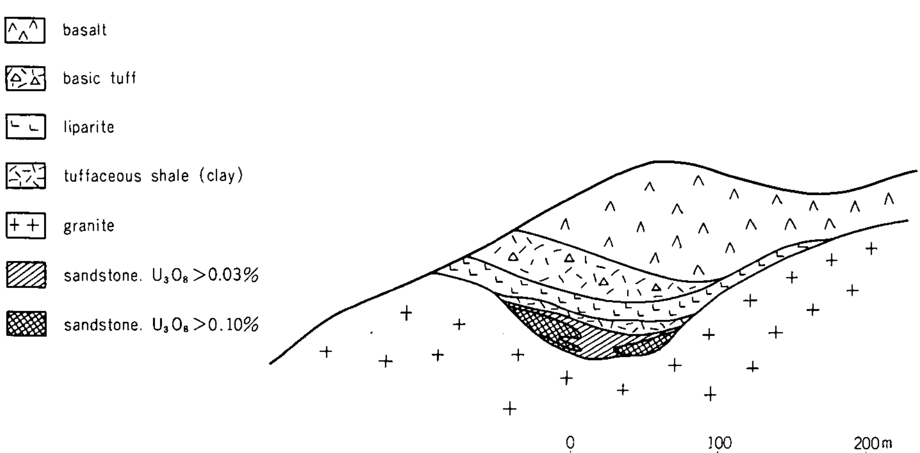

FIG.5. Schematic cross-section of channel structure.

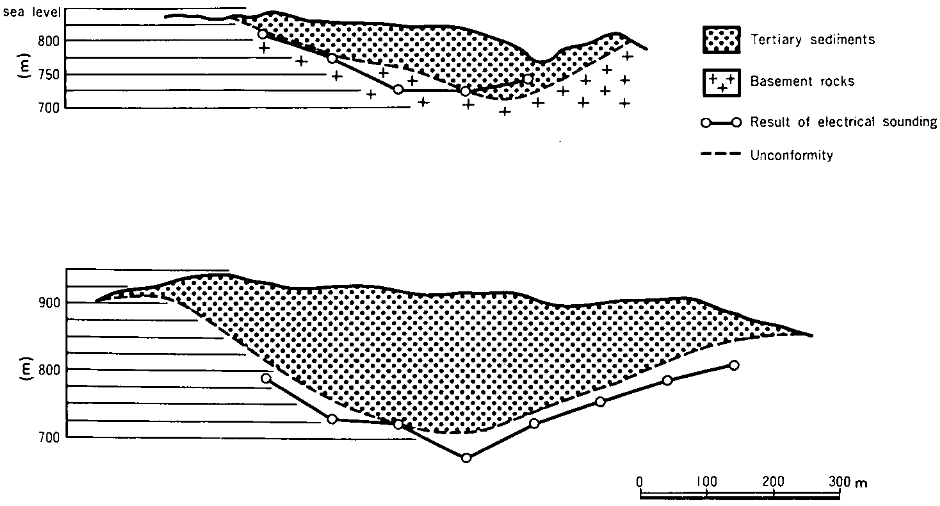

FIG. 6. Correlation of basement surface structure obtained by electrical sounding and drilling. The electrical sounding involves greater errors in areas with rugged topography.

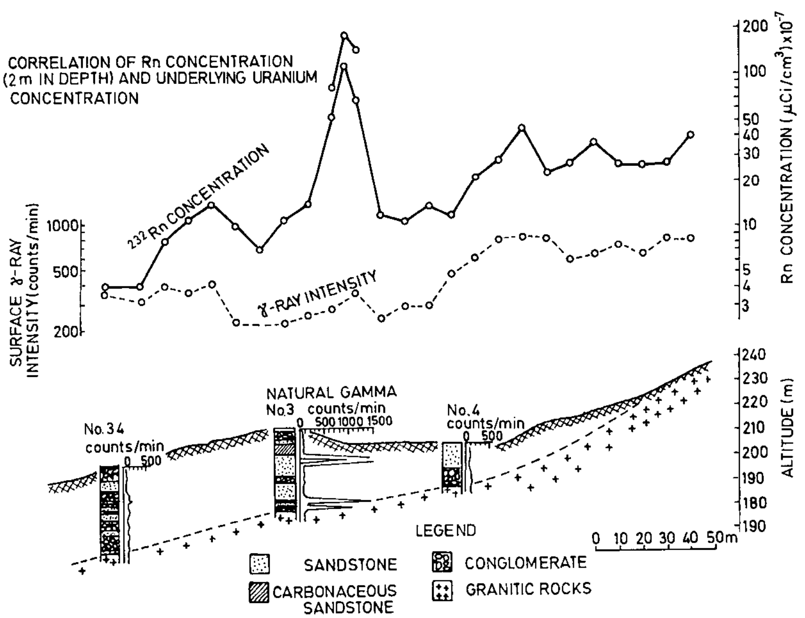

FIG. 7. Correlation of the radon method and logging results.

outline of the structure of the basement granite and it was not possible to distinguish the small-scale undulations of the unconformity because of the large variation of the travel-time curve caused by the surface topography. At the Tono area where the surface topography is more or less flat, it was possible to detect channels of 200 m wide and 25 m deep or smaller by seismic refraction surveys [4]. The gravity method proved to be reliable for reconnaissance-type surveys over a wide area. Electrical resistivity measurements were also carried out with satisfactory results [5].

It is thus not possible to generalize about the effectiveness of geophysical methods for these purposes, but it can be said that correct use of geophysical methods will be of tremendous value in locating the depressions of the unconformity.

8. RADON PROSPECTING

Prospecting by utilizing the radon content in the air contained in soils has not been used in Japan, but the method has been tested by the Geological Survey of Japan and has proven to be useful. As shown in Fig. 7, the data over a known ore body agreed very well with the shape which was confirmed by drilling [6]. This probably will be useful for the determination of the extensions of known deposits.

9. EXPLORATORY DRILLING

The extent of the ore bodies must be confirmed by drilling. The host rocks of these sandstone-type deposits, however, are always loosely cemented Neogene Tertiary sediments and it is not always possible to obtain cores. Thus, natural gamma-ray logging is important in determining the

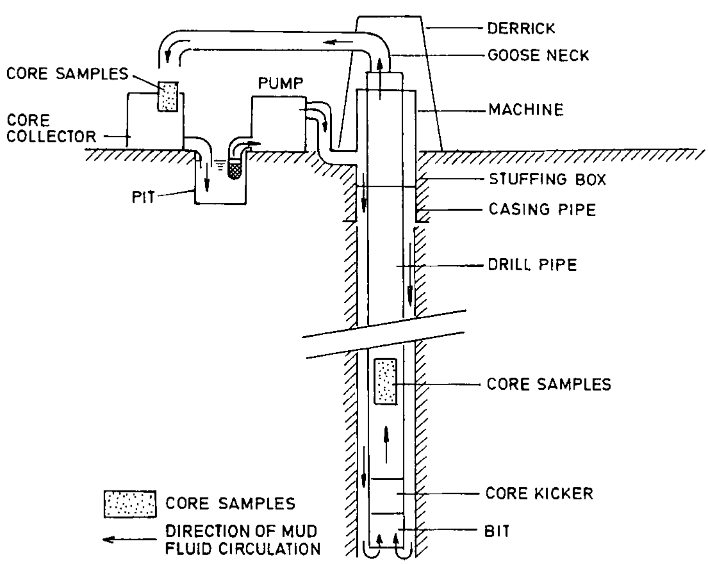

FIG. 8. Outline of the converse circulating drilling method.

grade and thickness of the mineralized areas. Gamma-gamma counting or the electrical resistivity method is used to determine the lithologic character of the host rocks.

On the other hand, core drilling would be preferable to determine the grade, specific gravity and other mineralogical characteristics of the ore bodies. With conventional rotary drilling and diamond drilling the average core recovery was less than 10% in the case of the sandstone-type uranium deposits in Japan. A newly developed technique by the PNC succeeded in obtaining almost perfect core recovery. The method involves diamond drilling using a large-size diamond bit (101 mm in outer diameter) and special mud fluid [7].

Recently, a method of continuous coring (converse circulating method) was developed jointly by PNC and Koken Boring Machine Co. In this method, the mud fluid is circulated down along the outer side of the drill pipe and up inside, bringing the core to the surface. A slight angle is made in the lower part of the pipe to cut the core to suitable size.

This method allows continuous drilling without changing the rods and the efficiency is increased about twofold. The outline of the arrangement is shown in Fig. 8.

10. CONCLUDING REMARKS

The methods used during the course of uranium exploration in Japan covering approximately 200 000 km^2 have been outlined very briefly. It is seen that all of the methods described are more or less orthodox and we are of the opinion that the combination of these methods with careful planning and execution will yield satisfactory results. It goes without saying that new methods should always be studied, tried, and, if effective, mastered and applied, and it is by no means our intent to underestimate the effectiveness of new and novel methods. But what we would like to stress here is that in cases where various factors such as funds, personnel, equipment etc. limit the application of various new methods, conventional methods can always be very reliable.

In spite of the special physical properties of the various ores, the factor of fundamental importance in uranium and other exploration work is a thorough understanding of the geological and geochemical environment.

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DISCUSSION

S. H. U. BOWIE (Chairman): Thank you very much, Mr. Shimazaki, for presenting this comprehensive review of your techniques in Japan and of recent developments, as well as for your summary, your views on the overall method of attack, which I think is important, and particularly for what you have to say to the peoples in the developing countries. This is the kind of experience that we are very glad to hear about.

J. A. FERNANDEZ POLO: Are the cross-sections we saw in the slides of certain deposits enclosed with tonguing or are they more equidimensional circular deposits? If they are tongued, is there at present any possibility for water circulation, or did such flow occur in the geological era prior to the present time.

Y. SHIMAZAKI: Yes, the water was circulating in geological times. What we think is that the source of uranium was in the underlying granite rocks and that uranium was leached by groundwater circulation and was deposited in the depression or channel-like structures of the granitic surface. There it occurs in the matrix of conglomerates which are very porous so that water can pass through. The deposition and precipitation of uranium was caused, we think, by reduction by pyrite or organic material.

H. H. ADLER: I would like to ask if you are familiar with the roll-type structures in the United States' deposits? Do you see any indications in your ore deposits of a similar type of recycling of the ore?

Y. SHIMAZAKI: I am not very familiar with your roll-type structures but from what I have read, I think there is very little resemblance — if there is any at all.

J. CAMERON: I think that the most similar deposits to yours in Japan are the ones in southwestern Turkey at Koprübasi. These deposits in paleo-channels and composed of very unconsolidated sediments appear to be very similar to yours.

H. H. ADLER: We do have an area in the United States which is in a granitic terrain and within the granite are low pockets in which the arkose material derived from the granite has been redeposited as a sediment. These are small and local and within these sands thin lignitic-coal deposits have also developed. These intervening sands also contain dispersed carbonaceous material and have developed uranium mineralization. Such deposits have been mined on a small scale. I think they are probably a bit similar to what you have described.

Y. SHIMAZAKI: Yes, especially in the Tonai district, the coal-bearing horizon or coal-bearing formation is called the Toki Kosine Bed, and that formation was mined a very long time ago for lignite. It is not in the area of uranium concentration but it is in the same horizon, and as you say it occurs with lignite.

J. F. DAVIS: It is significant that in one of the slides you showed tuffaceous sediments overlying the sandstone. I believe that in virtually every major sedimentary district in the USA there are invariably tuffaceous sediments overlying the sandstone deposits; whether this is a source for the uranium or for the leaching solution I do not know, but it seems a significant point to think about.

SURVEY OF PRESENT TECHNIQUES: CURRENT TRENDS AND FUTURE RESEARCH AND DEVELOPMENT REQUIREMENTS

METHODS, TRENDS AND REQUIREMENTS IN URANIUM EXPLORATION

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Abstract

METHODS, TRENDS AND REQUIREMENTS IN URANIUM EXPLORATION.

A prerequisite of well-planned reconnaissance programs is sound geological knowledge of the region under consideration. However, geological electronic techniques as well as those of geochemistry and geobotany all have a role to play in the discovery of uranium ore bodies. As the more accessible parts of the earth's crust are surveyed, more emphasis will be placed on aero-reconnaissance techniques capable of defining large, favourable though relatively inaccessible, areas and of detecting hidden ore bodies. Suggestions are made as to requirements and likely trends in the development of the more orthodox techniques as well as to relatively untried and novel search methods.

1. INTRODUCTION

The era of discovery of major uranium deposits with surface indications of radioactivity and located in the more accessible parts of the earth's crust is virtually at an end. Future ore finds are likely to be in relatively unexplored territory and in known favourable areas, but concealed below various types of overburden. There is thus a need to continue to develop what has now come to be recognized as orthodox prospecting techniques while at the same time planning the production of new instruments and methods of search that will assist particularly in the discovery of buried ore bodies.

A prerequisite of all well-planned reconnaissance programs is sound geological knowledge of the region under consideration. For, if uranium occurrences of economic significance are not present in an area, no amount of search using the most sophisticated techniques will prove to be cost effective. Geological criteria have been discussed by several authors in recent years and reference has been made to the more important contributions [1]. Geological criteria, though of paramount importance, will therefore not be discussed in the present paper.

2. ORTHODOX PROSPECTING TECHNIQUES

2.1. Aeroradiometric surveys

Aeroradiometric surveying can normally be recommended in circumstances where relatively large areas of favourable terrain are to be prospected and particularly if other geophysical techniques can be undertaken simultaneously. The method is also considered valid if funds are plentiful and quick results are required. The main controversy relating

to aeroradiometric surveying is whether or not to insist on gamma spectroscopy and if so what is the minimum satisfactory detector volume. Informed but extreme views are:

(a) Total count instruments with a NaI(Tl) detector volume of about 1500 cm^3 are adequate for most regional surveys undertaken at a flying height of 150 m and at a line spacing of 1000 m. This gives virtually complete cover and adequate sensitivity to detect an area of 50 m^2 at a grade of 0.2% $\underline{e}U_3O_8$ in favourable circumstances. A difficulty with the use of such equipment is the large number of anomalies detected. Experience has shown that the vast majority of these are due to resistate minerals such as zircon and monazite at the surface or to outcropping acid igneous rocks and can be discarded if a trained geologist flies in the aircraft.

(b) Fully stabilized gamma spectrometers with a NaI(Tl) detector volume of the order of 50 000 cm^3 are necessary if statistically significant count rates are to be obtained in the channels selected as being representative of U, Th and K. With smaller volume detectors, flying height must be reduced to 100 m or less which means that the line spacing for complete cover must be proportionally reduced, hence the cost per square kilometer is increased. The use of high-sensitivity gamma spectrometer equipment minimizes the geological contribution, but introduces considerable data-handling problems.

There is no doubt that the most suitable instrument is dependent on the nature of the survey envisaged and the type of aircraft to be used. Much smaller gamma spectrometer detector volumes could, for example, be used for follow-up investigations in a known anomalous region either using light fixed-wing aircraft or helicopters. An important feature of any instrument is that it should be stabilized so as to eliminate drift outside the selected spectral channels. Also the instrument should have spectral stripping facilities so that the degraded high-energy radiation of uranium and thorium daughters are not recorded in the potassium channel, thus giving a false impression of potassium abundance.

Aeroradiometric surveying is relatively expensive, costing from about £10/km^2, for sensitive total count instruments, to £30/km^2 for the most sophisticated gamma spectrometers. The method is not one of universal application, satisfactory results being dependent on a number of factors, the most important of which are:

(a) Ability of aircraft to maintain specified ground clearance to better than ±20% over the terrain to be surveyed.
(b) Climatic conditions suitable for relatively low flying.
(c) Terrain is not covered by glacial drift, aeolian sand or other material that would seriously attenuate or stop gamma radiation reaching the surface.

A feature of gamma spectrometers that merits special care is the fact that they detect ^{214}Bi and not ^{238}U or ^{235}U and, under certain conditions, ^{214}Bi may be removed from surface layers by normal leaching processes. This could well result in an important mixed uranium-thorium occurrence

being ignored because any anomaly would appear in the ^{208}Tl channel and be attributed to thorium.

The current tendence to quantify U, Th and K signals and to thereby decrease geological involvement is of dubious value. It cannot be expected that signal strength is necessarily indicative of the economic significance of an occurrence and although it is specially useful to know whether an anomaly is mainly due to uranium or thorium, most anomalies that cannot be discarded by a geologist in the aircraft should be examined on the ground.

2.2. Carborne radiometric surveys

Both carborne Geiger-Müller and scintillation equipment have proved successful in discovering uranium and will continue to be used in regions that can be traversed in a four-wheel-drive vehicle or where a reasonable network of roads exist. The trend is towards fully stabilized gamma spectrometers with a NaI(Tl) detector volume of at least 1500 cm^3 mounted on an extensible mast so as to provide better cover on either side of the route traversed. Such equipment can normally be provided with a probe on a few hundred metres of cable that can be used for detailed study of the U:Th:K ratio.

2.3. On-foot radiometric surveys

The mainstay of radiometric prospecting for uranium is a portable Geiger-Müller or scintillation counter. Thousands of these have been produced since 1945 and have been used in most, if not all, countries of the world. The tendency is for NaI(Tl) rate meters to replace Geiger-Müller instruments, which are still of importance for detailed follow-up work at surface, in trenches or underground — especially G-M counters with a beta-radiation facility. Many designs of equipment are available from different manufacturers and care is necessary in making the right choice of instrument, particularly if the equipment is for use in tropical, sub-tropical or arctic climes. Important features in the two first-mentioned circumstances are (1) sealing to prevent ingress of moisture and (2) a separate battery compartment to impede battery "sweating" adversely affecting the electronic components. Under all field conditions, adequate shock mounting for the detector and meter units is essential and the batteries should be of a type that is universally available. In arctic conditions mercury-type batteries are essential when working at temperatures below the freezing point. A crystal size of 30 cm^3 is adequate for most purposes, being capable of measuring changes in bedrock of less than 2 ppm $\underline{e}U_3O_8$ at a normal walking pace.

Portable gamma spectrometers developed in recent years are of particular value in regions where there is a likelihood of finding mixed uranium-thorium ores. Such instruments are more complex than scintillation counters and are of little value unless they are fully stabilized. The present dialogue concerning the number of channels desirable is largely dependent on whether or not geological knowledge is taken into consideration. An instrument with ^{214}Bi and ^{208}Tl total count facilities seems adequate in a portable instrument. Any potassium contribution can readily be assessed from the three measurements and from geological-mineralogical know-

ledge. Stabilized three- or four-channel instruments tend to be too complex and rather heavy for field use, though they have useful functions as transportable instruments.

2.4. Radon monitoring

The first specific method showing promise in detecting uranium under cover was that of measuring radon in ground air. Equipment was developed in the late 1950s but tested only on a limited scale. With the advent of renewed prospecting activities a decade later, new and more reliable instruments were introduced and perfected. Two types of equipment are currently available: one measures radon in ground air in the immediate vicinity of a shallow hole in which the probe is inserted; the other employs a pump which extracts air from the hole and surrounding overburden. The former method tends to be more specific, hence is suitable for defining relatively narrow mineralized structures. The latter is more appropriate for use in locating more deeply buried disseminated deposits. Good results have been achieved with both types of instrument through sand, peat, glacial drift and other relatively unconsolidated overburden.

Radon in water can also be measured and used as a means of indicating the presence of uranium mineralization. The method is particularly applicable in regions such as the shields of Canada or Scandinavia where there is an abundance of lakes and streams covering large areas.

Both ground-air and water-sampling techniques are subject to considerable variations due in the first case essentially to atmospheric and soil conditions, and in the second to sampling depth, temperature, pH, turbulence and dilution. Thus neither can be considered to be a quantitative method though it seems possible that developments in the measurement of radon in ground air together with the determination of helium could not only make the technique more quantitative but might permit estimates of the depth of uranium below the surface to be made.

2.5. Geochemical methods

Hydrogeochemical techniques have had a chequered history largely because of analytical difficulties and because radiation detectors have proved so successful in the location of ore bodies. In recent years, however, there has been a revival of interest in the sampling of stream and lake waters using neutron activation techniques of analysis. The method is specific, precise, rapid and relatively cheap, but it has the disadvantage that a reactor is necessary for sample irradiation. Limits of uranium detection are ≈ 1 μg/l and for sampling at levels above this value — at which no pretreatment of the sample is necessary — exploration costs are $<$£3/km^2 in the United Kingdom.

Hydrogeochemical reconnaissance is in some ways analogous in its scope to a primary aeroradiometric survey, its main value being in providing evidence of a major uranium province. But this approach is clearly more applicable in the case of terrain with abundant streams and lakes than in the case of desert or semidesert terrain. Water analysis for uranium is strongly recommended in all cases where stream sediment samples are being collected in the course of base metal exploration programs.

Uranium in stream sediments and soils can also be analysed by neutron activation techniques and this approach can be considered supplementary to water analysis especially in that it frequently gives more precise information on the location of uranium mineralization. None of the methods can be considered quantitative, because of the different solubilities and resistance to attrition of uranium minerals, and, in the case of water sampling, because of additional factors such as Eh, pH, chemical composition and degree of dilution.

2.6. Geobotanical or biogeochemical methods

Geobotanical methods have an application in the search for uranium, particularly in semidesert conditions where plants are deep-rooted and can transfer uranium from depths of as much as 20 m to their leaves. The main drawback of the method of foliage analysis is that suitable species of tree or shrub do not necessarily grow where they are wanted. In the case of the well-known vetch *Astragalus pattersoni*, which is found on the Colorado Plateau, its healthy growth is dependent on the presence of selenium in the soil, and, since selenium is commonly associated with uranium, the presence of the vetch can be regarded as an indicator of uranium.

The greatest promise for geobotanical methods lies in the exploration of forested country by the analysis of ashed foliage collected from identical species of trees or shrubs on a grid system. More practical experience of this method is necessary, but, from what work has been done, it would seem that trees growing near uranium deposits contain 2 to 200 times as much uranium in their leaves than ones growing in barren ground.

3. RELATIVELY UNTRIED TECHNIQUES

3.1. Indicator elements

Indicator elements are those associated with uranium, but occurring in greater amounts and hence easier to detect, or of greater mobility, thus giving a wider dispersion halo. Examples of chalcophile and lithophile elements commonly associated with uranium in nature are copper, lead, molybdenum, selenium, vanadium and arsenic. These elements have not as yet been found to be of much use as indicators, although lead has been used in tracing the extension of a known ore body and molybdenum values have been correlated with uranium-bearing structures in Scotland.

3.2. Radiogenic lead in nonradioactive minerals

Tests carried out in the USA and USSR have shown that nonradioactive minerals such as galena and pyrite carry abnormal amounts of radiogenic lead (^{206}Pb and ^{207}Pb) when they occur in proximity to uranium occurrences. This discovery could be of considerable value in the location of large-scale uranium provinces in which follow-up search could be undertaken. More analyses are required on a world-wide basis before this method can be established, but it is one that shows considerable promise.

4. NOVEL TECHNIQUES

4.1. Measurement of radiogenic heat

Considerable radiogenic heat is produced during the decay of uranium and its daughter products. A ton of uranium in secular equilibrium produces 730 000 cal. of heat per year so that heat flow to the surface over a uranium deposit should be considerably greater than normal. Two methods seem appropriate to test the validity of this suggestion:

(a) Use of thermal sensors to measure heat at the surface

(b) Application of high-resolution thermal infra-red scanning from an aircraft.

The latter approach has only just become a possibility with the introduction of equipment capable of detecting thermal changes of ±0.25°C at altitudes of up to 3000 m. This method may also have an application in detecting sulphide ore bodies undergoing oxidation.

4.2. Airborne geochemistry

Two methods of approach are also possible in the case of airborne geochemistry:

(a) Measurement of ^{222}Rn below an inversion layer using an ionization chamber or other detector system in an aircraft

(b) Collection and measurement of one or more decay products of radon, namely, ^{210}Pb, ^{210}Bi and ^{210}Po.

Solid decay products become attached to aerosols and could well be collected on a network of fine nylon threads wound on box frames and towed behind an aircraft or helicopter [2].

5. CONCLUSIONS

The main requirement of the future is the development of methods of detecting hidden ore bodies. Existing techniques will gradually improve through the normal processes of development – for example, by electronic miniaturization – thus scintillation counters will become smaller, lighter and more robust. Similar evolution will take place in the case of gamma spectrometers, whether portable or transportable. Together, all of the possible improvements will be adequate to ensure that new deposits with surface manifestations are discovered.

Geochemical measurements both on the ground and from the air are likely to increase in importance in aiding the detection of ore bodies just below the surface. For more deeply buried ore, radon measurements – possibly combined with those of helium – offer the best hope for the discovery of more deeply buried mineralization.

Further study is required in the use of indicator elements, in the measurement of radiogenic lead in non-radioactive minerals and in the measurement of radiogenic heat.

To ensure maintaining an adequate forward reserve of uranium, more research and development effort is required on a continuing basis. In countries where prospecting has continued for a period of time, the discovery rate in relation to the effort involved has fallen markedly and in these countries the greatest hope of increasing reserves lies in the introduction of new search techniques. In the relatively unexplored countries orthodox methods with normal development improvements will continue to be used for many years to come.

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DISCUSSION

H.H. ADLER: Mr. Bowie, you certainly have hit on several areas that we have at least in some superficial manner explored in the United States of America and have found to be wanting, perhaps owing to the fact that we did not give them sufficiently intensive exposure or perhaps for unknown geochemical reasons. I would like to comment on one or two of these areas, particularly in the realm of the untested and rather novel approaches. You mentioned helium as being perhaps useful in conjunction with radon analyses. Several years ago we attempted to ascertain the concentrations of helium in and around ore bodies, selecting the Gas Hills as our test area on the assumption that the helium concentrations would be larger over ore bodies due to the greater alpha concentration. We were very much disappointed to find that even where the radon anomalies were exceptionally high and where they could be associated with ore bodies in the near subsurface, we were unable to obtain any helium concentrations above those in air. We were quite unable to ascertain the reason. It occurs to me, however, that another aspect of this which could be looked into would be the helium as well as radon concentrations in groundwater. Since helium is quite soluble in groundwater, as is radon, one might expect that, in environments where there is a great deal of water introduced into the ground, the helium would be dissolved in the groundwater and this may account for the fact it is not available in the air entrapped in the sediments, as it does take time for helium concentrations to build up. We have not made any analyses of this but if one could detect helium anomalies in groundwaters, these would be quite effective because, as you know, radon has a very short half-life and its detectability near ore deposits is limited. If one were to use this technique as an indicator of approach or nearness to an ore body, helium might be much more effective than radon inasmuch as time is not a factor

in its existence and it could therefore be detectable over a longer period of time and over a longer distance.

As far as ^{206}Pb and ^{207}Pb are concerned, we have had problems there, too, but I think that this is largely a factor associated with the ages of our ores, which appear to be quite young. Recycling has evidently taken place in many in fairly recent geological times, and it takes a considerable period of geological time for sufficient ^{206}Pb and ^{207}Pb to build up before it can be extracted from the rock and detected by mass spectroscopy. Now the limitation here is, I understand, the concentration in the rock, because if you do not have at least a certain minimum concentration, the cost of applying this technique becomes rather large. The reason is that extremely clean laboratory conditions are required. Any extraneous introduction of lead will swamp out the amount of lead that you will be able to pick up from the rock itself; your reagents have to be cleaned meticulously before you can use this. The U. S. Geological Survey has had a considerable amount of experience in this field and they have recommended these scrupulous conditions. The cost of a lead-206/207 determination, commercially might be something on the order of $150 for a routine analysis and this may go up to $300 or perhaps much more depending on the problems you have in extracting the lead as the concentrations of lead in the sediments fall. Therefore, your comment about knowledge of the geological and geochemical conditions under which ore deposits could be found is very important. One could not use the lead approach as a random "wildcat" approach to prospecting – it just costs too much to examine any particular area of ground. It could, however, be used on a very local scale where one wanted quickly to assess in an area without indications of radioactivity the possibility that a suspected outcrop may represent a fossil ore deposit which is representative of a locus where ore at one time had existed and had subsequently been leached, and the outcrop of which was now completely barren of any trace of anomalous radioactivity. We have attempted to do this and consider the method possibly applicable under those circumstances.

S. H. U. BOWIE (Chairman): I think the important feature of helium is that it is an extremely mobile gas in comparison with radon which is a heavy gas, and I think it is most unlikely that it would be very effective in dealing with near surface deposits. What I am really thinking about are more deeply buried deposits. I also agree with your suggestion on the possibilities of helium concentrations in water. We have done quite a lot of work on this in South Africa where we actually measured the helium content in waters and found quite considerable percentages. I also agree with you on the lead-206/207 measurements, but again in your particular circumstances you are quite right in saying that the build-up of these two isotopes is not likely to be very great because of the youth of the uranium deposits. If you go to the areas like the Witwatersrad or Blind River where you have got an age of the order of 2000 million years, then there is a very considerable build-up of lead-206/207 even in normal rocks. Again I entirely agree with you that you would not use this as a wildcat method. We would use it with geological knowledge; but the costs of these analyses are coming down all the time, and although the cost is now on the order of $100 or $200, I am quite sure that within the next ten years, or less than that, we can do these for less than $50 per analysis, and perhaps cheaper than that. This is the kind of trend we can expect.

So, although I do not advocate this as a method we ought immediately to adopt for prospecting for uranium — it ought to be borne in mind. The method has the possibility of indicating whether or not a region is favourable to uranium mineralization.

M. MATOLÍN: I should like to refer to the part of your paper, Mr. Bowie, where you mention the measurement of radiogenic heat. I should like to ask whether you have some positive examples of this method, because we have tested this method several years ago and we came to the conclusion that usually the thermal field of a uranium body is totally depressed by the thermal field of underground waters.

S. H. U. BOWIE: Yes, I quite agree with this. This is a strong possibility. As I said earlier there is no technique which is a panancea, but what I had in mind here was an environment where one did not have the difficulties of underground water. In fact I know that this technique has been applied in a limited way and it does work; but I put this technique forward as a new one and not one on which we have any real experience. What I suggest we might do is more work on using existing techniques. We also intend to apply some of the newer methods which have become available in the past 5 to 10 years and which are highly sensitive.

AIRBORNE GAMMA-RAY SURVEY TECHNIQUES – PRESENT AND FUTURE

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Abstract

AIRBORNE GAMMA-RAY SURVEY TECHNIQUES – PRESENT AND FUTURE.

There are a variety of spectrometer systems available for commercial use. To use them in the most effective way it is necessary to consider the problems involved. Districts containing uranium mineralization generally fall within or on the margin of regions containing above-average abundances of all the radio-elements. These radioactive regions can be readily found by airborne surveys which measure only total radioactivity. Sometimes the mineralization controls within an area may be so well known that it is unnecessary to use spectrometer systems. In general it is advantageous to use the discriminating ability of a spectrometer to identify anomalies containing significant amounts of uranium. This selection of anomalies is most essential wherever the costs of ground work are high. The most sensitive spectrometers available are capable of measuring the mean ground level abundances of potassium, uranium and thorium, which can be expressed in conventional units of concentration. From an exploration viewpoint the most important parameters which can be measured are the relative concentrations of uranium to thorium and uranium to potassium. These are diagnostic for identification of zones of anomalous uranium concentration. Good counting statistics are essential to obtain meaningful ratio measurements. These are obtained by maximizing detector volume and minimizing ground speed of the aircraft. Minimizing flight elevation improves sensitivity for small area targets, but it entails closer line spacing for a given percentage coverage of an area. As a general principle, airborne gamma-ray surveys should be aimed primarily at finding target zones with linear dimensions of the order of hundreds or thousands of meters, where the mean enrichment of uranium at the surface may be only one or two parts per million higher than the surroundings. It can be shown that high-sensitivity equipment is most cost-effective for this purpose. The availability of fully corrected data, with a comprehensive display of all the parameters in profile and map form, is essential to extract maximum value from a survey with such equipment.

1. INTRODUCTION

An airborne survey is part of a spectrum of exploration techniques. In most circumstances, airborne surveys should form the first phase of work in a new area, and should be planned with the probable sequence of subsequent phases already in mind. Planning for such a survey should commence with an examination of everything that is already known about the area, covering all relevant aspects, from geology and mineral occurrences, to ground accessibility and climate.

Before reviewing the technicalities of airborne gamma-ray surveys it is important to consider the assumptions upon which an airborne survey is based. Justification for any airborne survey rests upon the assumption that for a given degree of effectiveness it can cover ground at a lower cost per unit area than can a surface survey. If this condition cannot be met, then there is no justification for it. The main advantage of an airborne survey is that it is possible to sample any predetermined proportion of a

region by an appropriate choice of line spacing and survey height and it is possible to ensure that a consistent standard of measurement is applied. Ground-level measurements in comparable detail are practicable only in easily accessible areas, and inevitably they require a large expenditure in man-hours. As the number of ground parties increases it becomes more difficult to have a consistent standard of measurement and automatic data reduction is difficult to apply. Thus a large number of man-hours will also be required for the preparation of data. Because of the many assumptions that must be made, it is not easy to provide estimates of the cost differential between ground and airborne surveys with comparable accuracy. From Geological Survey of Canada experience within the Canadian Shield, a grid of ground measurements on a 60-m grid using a portable gamma-ray spectrometer costs not less than \$780/km^2; airborne measurements with a high-sensitivity gamma-ray spectrometer flown on a 0.40-km spacing at 120-m clearance produce profiles and contour maps at a cost of \$31/km^2. Available ground control information indicates that the airborne system misses no significant radiometric features [1], but the ground work provides better spatial resolution and the opportunity to collect samples. Two men with one instrument engaged on ground work of this type cover about 2.5 km^2/month under average conditions, whilst the airborne measurements are gathered at the rate of 1.5 km^2/min. One aircraft with one crew would normally achieve a minimum of 800 line kilometres/d, or about 320 km^2 with lines at minimum spacing (0.40 km).

2. EFFECTIVENESS OF EXPLORATION METHOD

The effectiveness of any mineral exploration method is judged by its ability to recognize targets of economic interst and to eliminate anomalies caused by non-economic features. It must possess sufficient sensitivity to identify poorly exposed targets without losing its selectivity. This is particularly important for airborne methods employed over regions where ground access is difficult and therefore costly. An airborne survey which measures only the total radioactivity may be very sensitive but it cannot be selective. A gamma-ray spectrometer provides selectivity because of its ability to discriminate gamma energies and thereby measure the mean ground level abundances of potassium, uranium and thorium. Although total radioactivity can be measured at between 20-30% of the cost of a high-sensitivity spectrometer survey, this measurement provides a far greater number of anomalies for investigation on the ground because the results lack selectivity. Under these circumstances either the costs of ground investigation become excessive, or poorly exposed mineralization is almost certain to be overlooked. In this situation, money saved by embarking upon a total radioactivity airborne survey in preference to a high-sensitivity gamma-ray spectrometer survey may be a false economy.

3. GEOCHEMICAL CONSIDERATIONS

3.1. Selective concentration of uranium

Energy discrimination ability of a gamma-ray spectrometer provides the advantage of selectivity for the following reasons. Ore deposits re-

present anomalous concentrations of ore elements in the earth's crust and their existence is the result of some comparatively large process causing preferential concentration of the particular ore element. Thus, in all uranium deposits, uranium is concentrated relative to potassium, which is a major constituent of most rocks. The potassium content of most rocks falls between 0.1-10% whereas their uranium content ranges between 0.4 - 4 ppm. Before a uranium concentration can be of economic interest, it must reach 1000 ppm, i.e. it must exceed 4 ppm by a factor of 250. In contrast with potassium, thorium is not a major constituent of common rocks; it is normally only a trace constituent with an order of abundance about four times greater than uranium. Despite the geochemical similarities of uranium and thorium, it is characteristic of the great majority of economic uranium deposits that uranium is preferentially concentrated relative to thorium, and this preferential concentration may exceed the relative abundance found in normal rocks by several orders of magnitude. Experimental surveys over the principal types of Canadian uranium deposits show that the U:Th ratio is generally more specific for potentially economic uranium deposits than is the U:K ratio, although the latter does provide a wider target halo. For these reasons it is very important that the output from an airborne gamma-ray spectrometer system is used to provide measurements of the U:K and U:Th ratios.

3.2. Abundance ratio measurements

The importance of ratio measurements as a key to uranium exploration lies in the fact that in general the relative abundances of the three radioelements, potassium, uranium and thorium, remain relatively constant over a wide range of rock types [2,3]. It is only on rare occasions that some uncommon process results in the enrichment of one of these elements unaccompanied by enrichment in the others. Almost every such case merits investigation because of its rarity and because of the possibility that it points to a mineralization process.

One of the advantages of monitoring abundance ratios is that it provides a means of filtering count-rate anomalies, quite apart from identifying unusual radioelement distribution patterns where high absolute count rates may not occur. This is important since the measured count rate is influenced by the area of exposed rock, and the solid angle it subtends relative to the aircraft, as well as by the absolute abundances in the rock. It should be noted that an increase in absolute abundance, of uranium for example, is probably only a distant indicator of potential mineralization unless it is also accompanied by changes in relative abundance.

3.3. Regional abundance of uranium

Measurements made in Canada and elsewhere indicate that the districts which contain uranium deposits are generally characterized over ares of tens or hundreds of square kilometres by above-average radioactivity relative to their surroundings. No uranium deposits are known to occur within areas of below-average radioactivity. Therefore, because of their relatively low cost, total radioactivity measurements can serve a useful purpose by eliminating ground from further examination by more expensive radiometric methods. This preliminary reconnaissance can be done by

using widely spaced flight lines, for example at 8-km intervals. This spacing is based on surveys conducted over known uranium districts, which indicate that an 8-km interval would be sufficient to ensure at least two intersections of ground of above-normal radioactivity in each uranium area. Within each district of above-average radioactivity, identification of zones where uranium exhibits the greatest concentration requires a discriminating system. Other zones within a district may show enrichment in the other radioelements. In the Bancroft area of Ontario for example, the zone of maximum thorium enrichment does not coincide with the zone of maximum uranium [1].

3.4. Composition of surface materials

Gamma radiation in the range 1.46 - 2.62 MeV, which is of concern in most measurements of rock radioactivity, is quite strongly attenuated by rock and overburden. Approximately 90% of the total gamma radiation from a rock of density 2.7 comes from the upper 15 to 23 cm; from dry overburden with a density of 1.5, 90% of the radiation is received from the top 30 to 45 cm [4]. Thus radioactivity measurements only respond to radioelements contained in a relatively thin surface layer. It is therefore of vital importance before contemplating a survey in a region to establish that the surface materials are reasonably representative of bedrock composition. This means that in an area where overburden is predominant, which is defined as an area where it contributes more than 50% of the total ground gamma signal, overburden must be either residual or locally derived in order that surface-measuring radiometric methods can be useful. It also means that both outcropping rock and overburden must not have suffered removal of significant constituents by weathering. Uranium is most susceptible to this type of alteration especially under hot, humid conditions. However, it should be pointed out that since radiometric detection of uranium hinges on the measurements of ^{214}Bi, which follows radium and radon in the decay series, the recent weathering and removal of uranium is itself of no consequence as long as there is residual radium. Similarly the lateral migration of radium over distances of up to 50 - 100 m is of no consequence to airborne measurements, since this is the order of magnitude of spatial resolution. In fact, migration can be advantageous, by increasing the area of the target to be detected. The author is aware of no reliable evidence to indicate that under Canadian climatic conditions the migration of uranium and/or its decay products has presented any practical problems as far as airborne methods are concerned.

3.5. Geochemical haloes

Primary and secondary dispersion haloes in the vicinity of any type of mineralization provide the justification for all geochemical exploration techniques. Uranium is no exception to this and the primary haloes contribute to the existence of targets of regional extent. The success of airborne methods in locating zones which are host to mineral occurrences, and occasionally pinpointing the actual occurrences, stems from the existence of local dispersion haloes covering thousands of square metres. The average equivalent uranium content in these zones may be only 1 or 2 ppm greater than in the surrounding area [1], but with a sensitive system this

is sufficient to form an identifiable target for an airborne system. An airborne method should be designed to find these zones, rather than aim to locate actual uranium mineralization which may or may not be exposed at surface. In the early days of airborne radiometric surveys, undue attention was focused on the problem of locating "point sources". This stemmed from insufficient appreciation of geochemical considerations, combined with the inability of the then-available instrumentation to distinguish between the radioelements. The difficulty of locating single "point sources" from the air is not a serious matter because "point sources" seldom if ever occur in isolation.

4. METHOD

4.1. The gamma spectrum

The gamma radiation spectrum of the complex uranium and thorium decay series contains numerous photopeaks in the range of a few keV to 2.8 MeV. Potassium (^{40}K) possesses a single photopeak at 1.46 MeV. A recent review of the physics of natural gamma rays has been published by Adams and Gasparini [5].

For total radiation measurements, all photons are counted above some energy threshold set by the noise level of the photomultiplier assembly. It is important that this threshold does not drift, as the number of photons at the lower end of the spectrum increases very rapidly with decreasing energy. The key photopeaks for separating the uranium and thorium contributions are 1.76 MeV (^{214}Bi) for uranium and 2.62 MeV (^{208}Tl) for thorium. As mentioned above, there are many other photopeaks in each series, but they are either of too low energy (and thus strongly attenuated in air), or they cannot be readily resolved by NaI(Tl) scintillation detectors either from one another or from the Compton scatter background. Solid state detectors such as Ge(Li) could provide the necessary resolution to enable some of these peaks to be used, but the count-rate efficiency of such detectors is low and they suffer from the operational disadvantage of requiring continuous cooling by liquid nitrogen.

The comparative ease with which the key photopeaks can be resolved in excess of 600 feet above ground is illustrated by Fig. 1.

4.2. Instrumentation

There have been three different instrumental methods for obtaining spectral information from airborne (and ground) survey measurements:

(a) To obtain the count rate from the full spectrum in a series of discrete steps or channels (multichannel spectrometer).
(b) To obtain the count rates only from portions of the spectrum (windows) in the vicinity of photopeaks of interest (window spectrometer).
(c) To sum the counts from the spectrum in a series of overlapping steps by varying the energy threshold at which counting commences. For example, a threshold of 0.5 MeV would be used to measure the sum of K+U+Th; a threshold of 1.6 MeV would be used to measure U+Th, and a threshold of 2.4 MeV to measure Th alone (threshold spectrometer).

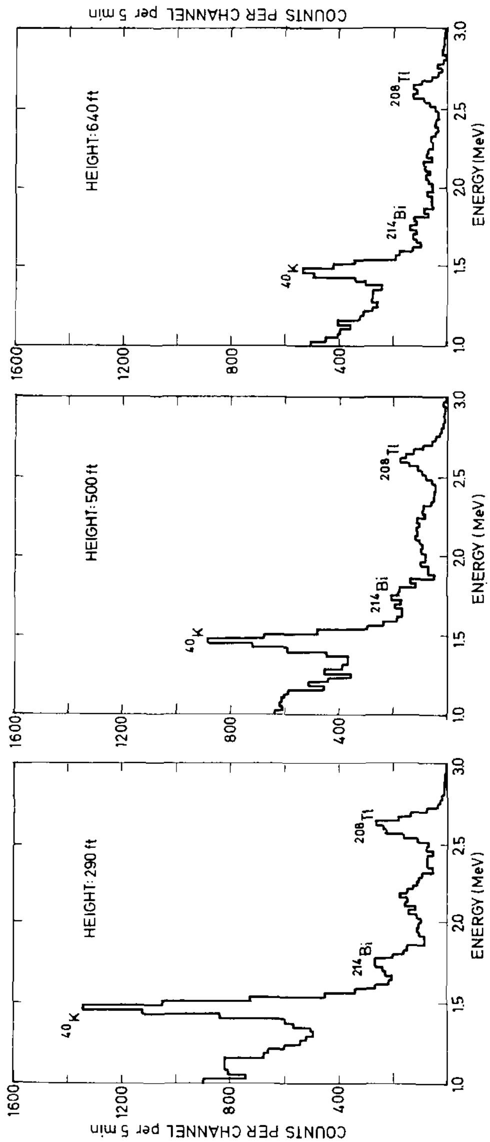

FIG. 1. Radiation spectrum at three different heights.

A multichannel spectrometer defines the full spectrum with resolution depending upon the number of channels used; because the full spectrum is being recorded, it can be reconstituted and corrected to allow for any small drift in calibration which may have taken place. The general form of the natural spectrum remains unchanged and only the spectral details, i.e. the relative heights of the peaks, change in the course of a survey. However, to record the full spectrum, magnetic tape must be used and the equipment is relatively complex because of the number of channels that must be recorded. There may also be design limitations with regard to permissible sampling rates due to the time required to read out data from the spectrometer to recorder.

Window spectrometers are the type most commonly used for airborne surveys. The use of four windows minimizes equipment complexity and at the same time avoids the collection of excessive data. However, it is not possible to reconsitute the spectrum to monitor calibration, so the system must either have some form of automatic stabilization or be very carefully designed to minimize electronic instabilities.

Variable threshold spectrometers are electronically somewhat simpler than the types discussed above, and are therefore cheaper. Because a wider portion of the spectrum is being utilized for the collection of counts, a variable threshold spectrometer exhibits a high count rate for a given detector size. However, because the characteristic spectral information relative to, for example, uranium, constitutes only a small part of the spectrum, the critical signal-to-noise ratio is not being significantly improved. Electronic stability for the variable threshold spectrometer is as important as for other types of spectrometer.

To minimize instability caused by drift in the high voltage supply and temperature dependent variations in the gain of the photomultiplier tubes, some spectrometer designs make use of automatic gain adjustment using an isotope of known energy as monitor. The two isotopes most commonly employed are ^{241}Am which is an alpha emitter or ^{137}Cs, a gamma emitter. Recently ^{57}Co has been advocated to avoid some of the disadvantages inherent in the other two. The gamma-energy equivalent of the alpha emission of americium is observed by different detectors at slightly different energies, and so is not satisfactory for multicrystal assemblies. Its gamma-energy equivalent is in the range 3 - 4 MeV which is above the range of natural terrestrial radiation. Caesium-137, with an energy of 0.662 MeV, has peaks which are below the photopeaks used for energy discrimination, and which encroach upon a portion of the spectrum normally wanted for total radiation measurements. Depending upon resolution of the detectors, the use of ^{137}Cs requires the total count threshold to be set at 0.8 MeV. Therefore, stabilization with ^{137}Cs entails a loss in total radiation sensitivity. Cobalt-57, newly introduced for stabilization purposes, avoids this problem. A recent review by Denham [6] of the present status of instrumentation designed for airborne radiometric surveys considers in some detail the use of ^{137}Cs and ^{241}Am as reference sources.

The principal cause of spectral instability is temperature change in the photomultiplier pre-amplifier assembly, and for this reason it has become common practice to maintain the whole detector system at a constant temperature by means of heating jacket and thermostat. Large changes in ambient temperature which may be experienced in airborne survey operations can affect other components of the spectrometer system, and this requires

TABLE I. AIRBORNE SCINTILLATION COUNTERS AND SPECTROMETERS AVAILABLE FOR PURCHASE

Manufacturer (country)	Model designation	Number, size, type of detector (diam. × length) (inches)	Type of spectrometer D: differential I: integral Ch: channel	Time constant or count times (s)	Recorder system (Ch: channel)	Power requirements	Spectrum stabilization	Compton correction facility
Abem (Sweden)	ABA 1501	One 5×6 or 10×5 NaI(Tl) crystal	D 4 Ch	Channel 1: 1, 2.5, 5, 10 s; Channels 2, 3, 4: 2.5, 5, 10, 20 s	5 Ch Analogue	12/24 V, DC; 50 W	-	-
Commercial Products Div., AECL (Canada)	CPD 322	Up to twelve 9×4 NaI(Tl) crystal Temp. regulated	D 128 Ch 4 integration regions	0.1 - 90 s; Dual timer	6 Ch Analogue and magnetic tape 7-track IBM	28 V, DC or 115 V, AC; 800 W with all options	-	x
	CPD 287	One or more 9×4 NaI(Tl) crystal Temp. regulated	D 128 Ch 4 integration regions	1 - 10 s count time; automatic for U: Th ratio	6 Ch Analogue or Digital	28 V, DC or 115 V, AC; 40 W plus recorder power	-	x
	CTD 192D	One 5×4 NaI(Tl) crystal for helicopter	D One integration region	0.3 to 30 s count time	Analogue or Digital	28 V, DC or internal rechargeable batteries	-	-
Exploranium (Canada)	DGRS-1001	Two to four 6×4 NaI(Tl) crystal	D or I Selectable from front panel ; 4 Ch	1, 2, 5 and 10 s each Ch	Analogue signal 0 - 3 V 4 Ch	24 V, DC; 35 W; 12 V, DC optional	^{137}Cs or ^{57}Co	x
	DiGRS-2000	Two to four 6×4 NaI(Tl) crystal	D or I Selectable from front panel 4 Ch	Count times of 0.1, 0.2, 0.4, 0.5 and 1 s	Digital 3 BCD characters/Ch Analogue signal 0 - 3 V per Ch	12 or 24 V, DC; 100 W	^{137}Cs or ^{57}Co	x
	DiGRS-3000	Two to four 6×4 NaI(Tl) crystal	D or I Selectable from front panel 4 Ch	Count times from 0.1 to 9.9 s in 0.1-s increments	Digital 4 BCD characters/Ch Analogue signal 0 - 3 V per Ch	24 V, DC; 100 W 12 V, DC optional	^{137}Cs or ^{57}Co	x
McPhar Geophysics (Canada)	AV-4	Up to three 6×4 or 8×4 NaI(Tl) crystal	I 4 Ch		4 Ch Analogue	23 - 30 V, DC; 12 W	^{241}Am	-
Nuclear Enterprises (UK)	NE 8424	Four 6×4 NaI(Tl) crystal	D 4 Ch	1, 2.5 and 5 s	Analogue	28 V, DC	-	-
Scintrex (Canada)	GIS-2	One to four 5×4 NaI(Tl) crystal	I Single Ch	2, 8 and 16 s	Single Ch	18 V, DC; 3 V, DC	-	-
	GDSA-4	One to four 5×4 NaI(Tl) crystal	D 4 Ch	1, 3 and 5 s	6 Ch Analogue	28 V, DC; 7 W	^{241}Am	x
	GISA-4	One to four 5×4 NaI(Tl) crystal	I 4 Ch	1, 3 and 5 s	6 Ch Analogue	28 V, DC; 7 W	^{241}Am	x

window- or threshold-type spectrometers to be monitored and adjusted either manually or automatically.

Table I, based on Hood [7], lists airborne scintillation counters and spectrometers currently available for purchase. It can be seen from this list that differential (window) spectrometers are more common than variable threshold (integral) spectrometers. Four 15×10-cm NaI(Tl) crystals provide the maximum detector volume normally offered and, although some digital recording systems are available, analogue systems are the most numerous at the present time (1972).

Until recently it has been the usual practice to record the radiation levels measured by scintillation counter or gamma-ray spectrometer as counts per second by means of a rate meter. This method, while relatively simple, is a major source of inaccuracy because of the difficulty in achieving a high degree of linearity in the rate meter and also because of the delayed response inherently associated with the time constant normal to this technique. For this reason, even at quite low survey speeds of 130 - 160 km/h, a radioactive target is passed before true peak intensities are recorded. Also, the fact that output from this type of counting system is in analogue form is a disadvantage if subsequent data processing or automatic compilation is required. The alternative to a rate meter measuring technique is to accumulate counts for precisely predetermined periods of time. Provided the aircraft's ground speed is known, each sample then relates to a known strip of ground. As the data from the analyser is accumulated pulse by pulse, the sum of the radiation provides a precise indication of the radioactivity of the terrain covered by the preset sampling period. The sum is in digital form and is thus suitable for recording on magnetic tape, or numerical display, and conversion into analogue form for visual strip chart recording.

4.3. Correction of data

Previous publications have shown how airborne spectrometric measurements can be directly related to the mean ground level abundances of the radioelements [1, 3]. However, to do this several corrections must be applied to the count rate as measured by the spectrometer. The first of these is subtraction of background radiation. Background radiation is made up of a cosmic contribution, a contribution from the structure of the aircraft and its equipment, and the most difficult to determine, a part arising from the presence of radon in the atmosphere. Bismuth-214, responsible for the 1.76-MeV peak used to estimate uranium abundance, is a decay product of radon. Table II shows the range of background values obtained during one summer's operation with the Geological Survey of Canada's high-sensitivity gamma spectrometer system. It has been observed that under fine summer weather conditions the atmospheric ^{214}Bi content measured at 125 m is normally at a maximum in the early morning and commonly diminishes by 10 - 15% as the day progresses, owing to atmospheric mixing. Variations in the ^{214}Bi background of the order of 10 - 20% have also been noted occasionally in the early morning within neighbouring parts of a survey area consisting of shallow valleys separated by low hills. Very high ^{214}Bi at ground level has been observed following a heavy thunderstorm [8].

The variability of atmospheric ^{214}Bi content is due to changes in atmospheric composition stemming from environmental factors: porosity and composition of ground, recent rainfall, wind strength, pressure gradient, etc.

TABLE II. OBSERVED ATMOSPHERIC BACKGROUND COUNT RATES USING GSC HIGH-SENSITIVITY SYSTEM, SUMMER 1970[a]

Channel	Σ	K	U	Th
Sampling interval	0.5 s	2.5 s	2.5 s	2.5 s
Maximum	325	130	70	
Median	260	107	50	38
Minimum	220	95	40	

[a] Although the background values are reported in terms of the adopted sampling intervals, the values were normally determined over a period of at least one minute.

The correct determination of the atmospheric-radiation ^{214}Bi contribution is of great importance, because of its variability and because it commonly exceeds the radiation contributed by ^{214}Bi in the ground. A background correction must be applied to airborne data before obtaining any quantitative data relevant to ground-level concentration.

The second step which must be taken in correcting data is to normalize measurements to a standard distance above ground. This is usually the nominal terrain clearance of the aircraft. Considerable attention has been given in published literature to deriving an ideal attenuation formula which would take full account of the effect of the geometry of the radiation source upon the attenuation value. It has been found from empirical observations over the Canadian Shield that for such topography where the relief does not normally exceed 200 m, a uniform exponential correction can be applied without causing any serious errors; greater errors arise if no correction is applied. In general, the consequences of applying a terrain clearance correction are to smooth data and to reduce count-rate highs and lows caused by variations in terrain clearance. Over the height range 50 - 250 m, the simple exponential function $N = N_0 e^{-\bar{\mu} H}$ is a close approximation to the observed attenuation. N is the observed count rate at height H, N_0 is the count rate at the nominal zero elevation and $\bar{\mu}$ is the experimentally determined overall attenuation coefficient (which includes a Compton scattering component). The relation between count rate and height is given more correctly by the expression

$$N = N_0 E_2 (\mu_a H)$$

where E_2 is a tabulated function known as the exponential integral of the second kind, μ_a is the attenuation coefficient of air, and H is height.

Whilst the attenuation over the range 50 - 250 m calculated according to this more complex formula is not significantly different from that given by Grasty's simpler exponential expression, the second formula indicates a more rapid fall-off of count rate close to the ground and correctly describes the relationship between observed ground and airborne data [9]. Within the operating range 50 - 250 m, the half-height, i.e. the distance over which the count rate is reduced by half, is approximately 100 m for radiation in the 1.46-MeV window and 120 m for radiation in the 1.76 and 2.62 MeV

TABLE III. EXPERIMENTAL OVERALL ATTENUATION COEFFICIENTS

Radiation	MeV	Window	$\bar{\mu}$ (ft^{-1})	$\bar{\mu}$ (m^{-1})
^{40}K	1.46	1.36 - 1.56	2.3×10^{-3}	7.5×10^{-3}
^{214}Bi	1.76	1.66 - 1.86	1.7×10^{-3}	5.6×10^{-3}
^{208}Tl	2.62	2.42 - 2.82	1.7×10^{-3}	5.6×10^{-3}
Σ		0.4 - 2.82	2.0×10^{-3}	6.6×10^{-3}

windows. The similarity of the attenuation coefficient for two dissimilar energies is apparently due to the Compton contribution from higher energy thorium radiation compensating for the greater attenuation of primary 1.76-MeV radiation. Values for $\bar{\mu}$ relating to the simple exponential formula are given in Table III. For first-order approximations the attenuation coefficient can be taken as 20% per 30 m. It is important to emphasize that it is only meaningful to apply a height correction to results obtained with a system which provides an adequate count rate. If one standard deviation for a mean count rate is much greater than 20%, there is little purpose in attempting to correct for clearance deviations of less than 30 m.

The third correction which must be applied to data is to compensate for Compton scattering within the detector crystals, which contributes to both "uranium" and "potassium" count rates. Scattered "thorium" radiation contributes counts to both the lower energy "uranium" and "potassium" channels whereas scattered "uranium" contributes to the "potassium" channel only. The precise value for Compton scattering corrections depends upon the window width employed, and also upon the size, number and spacing of radiation detectors. Typical values are shown in Table IV taken from Grasty and Darnley [10], together with the formulae used for correction.

It should be noted that because the apparent attenuation factor employed for correcting "uranium" contains a Compton scattered contribution from "thorium", the apparent "uranium" height attenuation factor will be affected by the U : Th ratio of the ground beneath. It is therefore important that for normal use the attenuation factor adopted for "uranium" should be established over ground which has the normal relative abundance of uranium to thorium (0.25). However, it should be borne in mind that where substantial variations in terrain clearance occur, the use of an average apparent attenuation factor for "uranium" will have the following effect. Over ground with a low abundance of uranium relative to thorium, the height correction will tend to exaggerate apparent uranium concentration at high terrain clearances, and underestimate at low clearances. Over ground where uranium has a high abundance relative to thorium, the average attenuation factor will underestimate uranium at high clearances and exaggerate it at low clearances. Therefore ideally the attenuation coefficient should be varied continuously with changes in the U:Th ratio of the ground. Taking the overall uncertainties of the correction into consideration, and in particular those due to poor counting statistics, such sophistication does not now appear to be generally warranted. Results obtained in mountainous terrain would benefit most from a more elaborate correction, but it should be remembered there is no safe correction for a deficiency of counts.

TABLE IV. FORMULAE AND SAMPLE VALUES FOR COMPTON SCATTERING CORRECTIONS

$$N_{Th\,corr.} = N_{Th} - Bgd_{Th}$$

$$N_{U\,corr.} = N_U - Bgd_U - \alpha N_{Th\,corr.}$$

$$N_{K\,corr.} = N_K - Bgd_K - \beta N_{Th\,corr.} - \gamma N_{U\,corr.}$$

where N_{Th}, N_U and N_K represent the observed count rates in the relevant windows, Bgd is the background count rate, the subscript indicating the window.

α = counts in the U window per count in the Th window

β = counts in the K window per count in the Th window

γ = counts in the K window per count in the U window

SAMPLE VALUES

	Helicopter 3 (5×5) in. NaI	Skyvan 12 (9×4) in. NaI
α	0.43	0.35
β	0.62	0.33
γ	0.91	0.56

4.4. Statistical considerations

The laws of statistics govern the accuracy of all measurements of radioactive decay. Counting statistics should, therefore, be the prime factor in determining design parameters for any gamma-ray measuring system. The formula $\sigma = \pm\sqrt{N}$ shows the magnitude of uncertainty represented by one standard deviation, for any measuring time during which N counts are accumulated. To arrive at the statistical accuracy of corrected count rates, background count rates must be taken into consideration in conjunction with the total observed count rate and the Compton correction factors. The appropriate formulae are given in Table V. The full significance of these statistical considerations is not appreciated until actual values are substituted in the formulae, when the magnitude of the uncertainties associated with even high-sensitivity systems become apparent. This can be demonstrated by considering the count rates obtained with a high-sensitivity system in regions of relatively high and relatively low radioactivity respectively, and also with a low-sensitivity system in a low-radioactivity region. Table VI shows the standard deviations of the mean count rate obtained (a) in a region of above-average radioactivity when the atmospheric radioactivity is low (favourable situation) and (b) in a region of low radioactivity when the atmospheric radioactivity is high (unfavourable situation). These results clearly indicate the fact that uranium is the most difficult of the radioelements to measure, partly because of the low initial count rate but also because of the presence of atmospheric ^{214}Bi and the necessity to apply a thorium-dependent correction. It is a reasonable expectation that a gamma-

TABLE V. FORMULAE FOR DETERMINING STANDARD DEVIATION OF CORRECTED MEASUREMENTS

$$\sigma_{Th} = \left[N_{Th} + \frac{Bgd_{Th}}{T}\right]^{\frac{1}{2}}$$

$$\sigma_{U} = \left[N_{U} + \frac{Bgd_{U}}{T} + \alpha^2\sigma_{Th}^2\right]^{\frac{1}{2}}$$

$$\sigma_{K} = \left[N_{K} + \frac{Bgd_{K}}{T} + \beta^2\sigma_{Th}^2 + \gamma^2\sigma_{U}^2\right]^{\frac{1}{2}}$$

$$\sigma_{\Sigma} = \left[N_{\Sigma} + \frac{Bgd_{\Sigma}}{T}\right]^{\frac{1}{2}}$$

Count rates are counts per sampling interval.
T = number of intervals over which background was accumulated.

ray spectrometer system should be able to detect a doubling in the concentration of ground-level ^{214}Bi with 95% certainty (i. e. 2σ) under all circumstances, and it can be seen that even the high-sensitivity system does not quite meet this requirement in the unfavourable situation. To pursue this argument, if one standard deviation greater than 50% is arbitrarily considered as unacceptable, it can be seen that the low-sensitivity gamma-ray spectrometer system cited in Table VI is only suitable for providing total-radiation and potassium measurements.

Of course, by modifying counting times, flying heights and speed, the count rate limitations set by the volume of the detector system can be minimized to some extent, and completely avoided if spatial resolution is degraded. However, if the latter course is pursued too far, a point is rapidly reached where the system becomes useless as an exploration tool. The interrelation of the design and operational parameters of a gamma-ray spectrometer system is discussed in a subsequent section.

4. 5. Conversion to element concentration

With background, terrain clearance and Compton scattering corrections applied, counts in the energy-discriminated channels can then be converted directly to element abundances. The conversion factor depends on the dimensions and volume of the detector system, window width, sampling time and flying height. Although airborne radiometric survey measurements have not usually been expressed in units other than counts per unit time, there is a strong argument for requiring them to be expressed in terms of mean ground level abundance of the respective radioelements. A measurement reported in terms of count rate is peculiar to a particular survey. Count rates from two different surveys cannot normally be compared in any meaningful way and so maps based on a reproducible unit cannot be compiled. While there are assumptions and problems involved in converting count rates to element abundance, the advantages of such a presentation outweigh the disadvantages, and the act of making the correlation encourages careful consideration of the problems involved. At such time as regional

TABLE VI. STANDARD DEVIATIONS FOR SOME ACTUAL MEASUREMENTS

Channel Sampling interval	Σ 0.5 s	K 2.5 s	U 2.5 s	Th 2.5 s	U: Th Ratio
GSC high-sensitivity system					
Favourable situation					
Atmospheric background	220	95	40	38	
Corrected count rate	1000	400	50	150	0.33
1σ	35	25.2	13.6	13.9	0.09
1σ (%)	3.5	6.3	27.2	9.3	28.5
Unfavourable situation					
Atmospheric background	325	130	70	38	
Corrected count rate	400	150	20	30	0.66
1σ	27	18.7	11	8.5	0.41
1σ (%)	7	12.5	55	28	62.5
Low-sensitivity system					
Unfavourable situation					
Atmospheric background	33	13	7	4	
Corrected count rate	40	15	2	3	0.66
1σ	8.6	5.9	3.5	2.7	1.29
1σ (%)	21.4	39.3	172	90.6	195

Note: 1. (a) Favourable situation: above-normal ground radioactivity, figures based on NW portion of Churchill geological province, Canadian Shield [13].
Low background from Table II.

(b) Unfavourable situation: below-normal ground radioactivity, figures based on central portion Superior geological province, Canadian Shield [13].
High background from Table II.

2. Low-sensitivity system: assumed 1/10 detector volume of high-sensitivity system, other parameters the same.
(Background values assumed based on 25-s sampling time.)

airborne radiometric maps are made in the manner now practiced for aeromagnetic surveys, such standardization will be essential.

In Canada, the correlation between corrected airborne count rates and mean ground-level element abundance has been approached by the Geological Survey of Canada in two ways [1]:

(a) Calibration flights at known heights over a carefully selected strip of ground which has reasonably uniform known abundances of the radioelements, determined by systematic ground measurements.

(b) Systematic ground measurements over different sites of suitable size and homogeneity representing different levels of radioactivity within a survey area.

Empirical methods have been used up to now to establish the element abundance correlation in order to avoid a premature commitment to any particular attenuation formula.

Table VII is based on results obtained by the GSC Skyvan spectrometer system and shows the relationship between element concentration at ground level and count rate at a height of 120 m above ground for the window widths specified in Table III. It again emphasizes the comparatively low count rates obtained even with a large detector volume (50 071 cm^3) and underlines the necessity for accumulating counts over a sampling period longer than 1 s. For this system, 2.5 s has been adopted as standard to obtain a compromise between adequate ground resolution and counting statistics.

Table VII also shows the magnitude of one standard deviation in terms of element abundance for a high-sensitivity and a low-sensitivity system. The standard deviations are taken from Table VI. For reasonable certainty in the evaluation of a measurement it is necessary to consider two standard deviations. This limits the effective sensitivity of the best system to about 0.25% K, 1 ppm eU, 2 ppm eTh, with the low-sensitivity system inferior by a factor of $\sqrt{10}$. These sensitivities relate to single sample intervals, at an altitude of 120 m. Field studies indicate that it is highly desirable to have a sensitivity of better than 1 ppm eU combined with a spatial resolution of better than 150 m, to have a satisfactory uranium exploration system.

TABLE VII. ELEMENT CONCENTRATION – AIRBORNE COUNT RATE CORRELATION

GSC Skyvan system with 50 070-cm^3 detector volume at 120 m [1]

1% K = 200 counts/2.5 s

1 ppm U = 25 counts/2.5 s

1 ppm Th = 12.5 counts/2.5 s

Accuracy of measurement (1σ probability)

	K (%)	U (ppm)	Th (ppm)
High-sensitivity system			
Favourable situation	± 0.125	± 0.5	± 1.1
Unfavourable situation	± 0.1	± 0.4	± 0.7
Low sensitivity system			
Unfavourable situation	± 0.33	± 1.4	± 2.2

4.6. Standardization of total count surveys

There is a requirement for standardizing the output from total count radiometric surveys in addition to standardizing the results from spectrometric surveys. The unit of standardization for total count surveys is more difficult to decide than the unit for spectrometric surveys. From a geological point of view it can be argued that because potassium is the most abundant radioelement, and because normally there is only a narrow range of variation in the proportionality between potassium, uranium and thorium content in rocks, an equivalent potassium unit would be the most geologically informative way of expressing the measurements. This unit would have to assume a fixed proportion of K : U : Th, and would give a correct estimation of potassium content in the ground wherever the average proportionality applied.

5. COMPARISON OF SYSTEMS

5.1. Equipment effectiveness

An airborne survey system comprises all the equipment necessary to perform a survey, including the aircraft, height-, position-fixing and radiometric instrumentation. In planning a radiometric survey, a number of parameters can be varied, namely detector volume, flying height, airspeed and line spacing; it is assumed that spectral window widths have optimum settings which should remain fixed whatever the other operational parameters of the survey, whilst the ratemeter time constants, or sample integration times, are optimized after other parameters have been decided. Often a choice of equipment is available for a survey, and some performance criterion, apart from cost, is desirable to assess the comparative effectiveness of different systems. Counts per unit distance provide a useful basis for measuring overall effectiveness. Factors which influence this value are the detector volume, mean height above ground and mean ground speed. Systems can be compared with respect to their effectiveness for both large and small sources. The best index of comparison between systems is provided by the square root of the normalized count rate for each system since it is the relative magnitude of their standard deviations which determines the sensitivity of each system to changes in element concentration. The square root of the normalized count rate is called the figure of merit of the system.

It can be demonstrated that, given a minimum crystal dimension of 10 cm, the count rate from a NaI(Tl) detector assembly is approximately proportional to its volume. Table VIII gives the standard deviation of the relative count rates per unit distance for a number of survey systems. Various commercial systems are designated by the letters A to D. In this example, all are compared against the Geological Survey of Canada's Skyvan-mounted spectrometer system which is rated as 10. It can be seen that for large-area targets, the large detector volume of the Skyvan system provides a distinct advantage: for small targets the low terrain clearance employed for some of the commercial surveys compensates for their small detector volume. However, it has been pointed out in a preceding section that a large surface area of weak enrichment is a more realistic

TABLE VIII. SPECTROMETER SYSTEMS – FIGURES OF MERIT

System	Detector: Size (diam. × thickness) (cm)	Detector: Volume (cm^3)	Terrain clearance (m)	Speed (km/h)	Merit (normalized count)$^{\frac{1}{2}}$: Large area	Merit (normalized count)$^{\frac{1}{2}}$: Small area
GSC mapping	12 (22.9 × 10.2)	50 071	122	193	10.0	10.0
GSC reconnaissance	6 (22.9 × 10.2)	25 028	152	225	6.0	5.2
GSC helicopter	3 (12.7 × 12.7)	4 835	76	48	7.1	10.0
Commercial A	4 (15.2 × 10.2)	7 425	91	145	4.9	5.0
B	1 (20.3 × 10.2)	3 294	38	128	4.0	10.0
C	1 (15.2 × 12.7)	2 311	46	97	3.75	6.7
D	3 (15.2 × 10.2)	5 573	46	209	4.0	7.1

Merit calculated from:

Large area $$\left[\left(\frac{V_X}{50\,071}\right)\left(\frac{193.1}{S_X}\right)\left(\frac{100}{e^{-\bar{\mu}(121.9-H_X)}}\right)\right]^{\frac{1}{2}}$$

Small area $$\left[\left(\frac{V_X}{50\,071}\right)\left(\frac{193.1}{S_X}\right)\left(\frac{(121.9)^2}{H_X^2}\right)100\right]^{\frac{1}{2}}$$

where

V_X = volume of detector crystals (cm^3)

S_X = mean ground speed (km/h)

H_X = mean terrain clearance (m)

$\bar{\mu}$ = 5.6×10^{-3} (m^{-1})

target for airborne exploration than is a localized "hot-spot", and so sensitivity to low-concentration, large-area targets is the most desirable feature of any system which is intended for use on a large scale. If required, a small installation in a low-flying helicopter can be used during a later phase of exploration to find "hot-spots". One factor to be considered in connection with very low-level surveys (50 m), apart from their hazard, is that they are strongly influenced by the inhomogeneity of surface details, that is to say outcrop distribution, surface geometry, and the presence of small patches of water. Ratio measurements provide the best means of minimizing these factors which will have a substantial effect on absolute count rate. At 60-m flying elevation, approximately 65% of 2.62-MeV radiation originates within a radius of 90 m of the aircraft. At 120-m elevation, the same percentage originates within a radius of 150 m of the aircraft. A diagrammatic representation of the radiation yield at different heights as a function of source influence is given in Ref. [11]. It is self-evident that the lower the terrain clearance, the closer the line spacing must be to achieve comparable search effectiveness.

For the purpose of conducting regional surveys over large areas, considerations of safety and ease of navigation make it undesirable to fly at

a height of less than 125 m. Therefore, regional surveys do not allow much choice in this parameter.

From the count rates quoted in Table VI it can be seen that even the most sensitive systems available do not possess any margin of surplus sensitivity for the measurement of potassium, uranium and thorium. Total radiation is the only measurement for which equipment now available can provide more than adequate sensitivity. The total count rates given in Table VI are based on 0.5-s sampling times, whereas the sampling times in the energy-discriminated channels are 2.5 s. In 0.5 s an aircraft travelling at 200 km/h covers approximately 30 m; in 2.5 s it covers approximately 150 m. The latter sampling time at this air speed provides adequate spatial discrimination for a total count system, and therefore one-fifth of the detector volume employed for a high-sensitivity spectrometer system is sufficient for a high-sensitivity total count system, i.e. 10 000 cm^3 is required. Before engaging in any large-scale reconnaissance survey it is advisable to carry out limited ground investigations at accessible places within the area, to verify that the parameters which are going to be measured are within anticipated limits. If they are not, then clearly the specifications for the survey should be modified accordingly.

5.2. Cost effectiveness

Information available from contractors in North America shows that gamma-ray spectrometer surveys are available at from \$3 to \$12 per line kilometre. The lower cost relates to low-sensitivity equipment with simple result presentation, whereas the higher cost relates to the use of high-sensitivity equipment with a very comprehensive presentation of results. It is clearly important to have some means of judging whether the additional cost of more sensitive equipment is justified by superior performance. One way of assessing the cost effectiveness of a system is by considering its figure of merit relative to its cost per unit area. More elaborate ways of measuring cost effectiveness can be devised, but this one serves to identify the critical features. On simplistic economic grounds, the use of a system with a low figure of merit (calculated according to Table VIII) might be justified if the costs were sufficiently low. The determining factor in the choice between competing systems is the ratio of their line-kilometre costs at which their cost effectiveness is equal:

$$\text{Cost effectiveness} = \frac{\text{Figure of merit}}{\text{Cost per unit area}}$$

The choice of systems will depend upon tendered costs. For example, consider the "GSC mapping system" versus "Commercial B" as given in Table VIII. Let x be the line kilometre cost of the former and y for the latter. The former is flown at 120-m terrain clearance and complete coverage of an area is obtained with a line spacing of 0.4 km. "Commercial B" is flown at 40 m and complete coverage would require a line spacing of 0.20 km. Taking the figure of merit values from Table VIII, for a large area target:

$$\frac{x}{y} = \frac{10 \times 5}{4 \times 2.5} = 5$$

for a small target:

$$\frac{x}{y} = \frac{10\times 5}{2.5\times 10} = 2$$

This means that if the purpose of a survey is to locate large area targets with small enrichment factors, then the "Commercial B" system would have to be more than five times cheaper than the high-sensitivity system for it to be more cost effective. However, for finding small targets, system "B" need only be less than half the line mile cost of the high-sensitivity system for it to be more cost effective for these requirements.

In most circumstances, the maximum line-kilometre cost differential between high- and low-sensitivity systems would not exceed a factor of four. It must be stressed that insofar as an airborne gamma-ray spectrometer survey forms only the first part of an exploration operation, it is not necessarily good overall economics to have an apparently favourable cost-effectiveness ratio if the effectiveness of the chosen system is low.

6. RESULTS

6.1. Total gamma radiation surveys

In the past, total radiation surveys have been recorded almost entirely on analogue strip charts, and for compilation purposes it has not generally been thought necessary to make any corrections, nor has it been practicable to do so. However, for compilation into contoured maps, especially where these may relate to large areas and the data may be collected over a period of days, weeks or even months, it is necessary that there should be corrections for the inevitable variations in natural atmospheric background radioactivity. Variation in cosmic background and man-made radioactivity may also occur. Corrections for terrain clearance variations are also highly desirable. Recently, electromechanical equipment for digitizing analogue records has become available and some surveys are now being processed in this way so that corrections can be applied by digital computer prior to contouring. Direct digital recording avoids the errors inherent in manual digitizing.

6.2. Spectrometric surveys

To obtain maximum values from spectrometry data, it is necessary that it should be fully corrected and used to prepare both corrected profiles along the flight lines, which are the primary source of information for further detailed exploration, and also contour maps which indicate the regional pattern of radioelement distribution and provide the most convenient means of correlating with other forms of earth science data.

The first commercially available spectrometers contained no internal means of making corrections and relied upon analogue recording charts. Consequently, only grossly simplified data presentations were possible, and contouring was not attempted or was limited to thorium only. One of the most common forms of data presentation has been to use a symbol superimposed on a flight line plan to indicate an anomaly which exceeds by

some given factor an arbitrary background value. This type of inexpensive presentation is unsatisfactory from several points of view. Firstly, it is somewhat subjective; secondly, since the instrumentation being used has no provision for Compton scattering correction there is no indication of the extent to which uranium anomalies are a consequence of high associated thorium values. Thirdly, the concept of background as used in these situations relates to the average overland radiation level. It thus ignores the information which the overland radiation base level can provide about the general geochemical environment. Fourthly, since no terrain clearance correction is applied, the user of such data must assume that the clearances were within acceptable limits and that the anomalies were not caused by topographic highs. This assumption may be incorrect.

Slightly more information is conveyed if the uranium count rate in the anomaly peak is shown alongside the uranium background (used in the same sense as the first example) and the thorium value in the anomaly is also shown against its background value. However, it is important to indicate whether a Compton scattering correction is being applied to the uranium estimate.

A further elaboration is to contour thorium content and add this to the display of anomalies. This takes account of the fact that the thorium count is usually more reproducible and statistically more significant than the uranium count and it can therefore be used as an aid in interpreting geology.

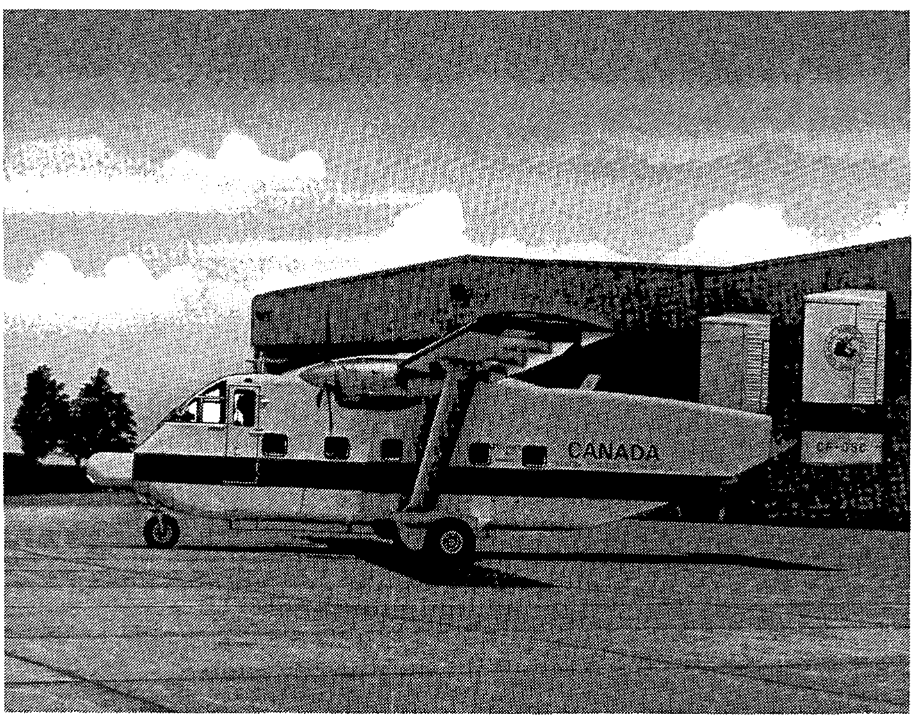

FIG. 2. The Geological Survey of Canada's Skyvan aircraft used for carrying high-sensitivity gamma-ray spectrometry equipment.

Another type of presentation is known as "offset profiles". The strip chart data is transferred from the original flight record onto a map and plotted alongside the flight lines. Ideally this allows the user to see the relationship in radiometric pattern from line to line and link up features which he considers similar. Allowance should be made for the lag in plotted positions due to the time constant of the rate meter. If this is not done, anomalies on adjoining lines will be laterally displaced relative to one another wherever adjoining lines have been flown in opposite directions. This needlessly complicates reading of the results.

With the exception of this last type of presentation in which there are separate offset profile maps for total count, potassium, uranium and thorium, the commonest form of presentation has hitherto consisted of only one map compilation to minimize costs. It must be emphasized that an elaborate presentation of data is not warranted if either the counting statistics of a spectrometer system or its stability are inadequate, but assuming that these requirements are met, then automatic data processing is the only practical solution to the problem of complete and informative presentation of results. Too many commercial presentations of spectrometer data show that, in general, satisfactory standards of presentation have not yet been achieved. Information necessary to judge the quality of data collection is not usually available, and only a portion of the data is being presented. Inadequacies of both instrumentation and data presentation are only partly economic and technical in origin. They are also a reflection of lack of knowledge by users about the capabilities and limitations of airborne radiometric techniques. As in many other fields, consumer education is a prerequisite to obtaining value for money expended.

Appendix I contains a sample specification for a high-sensitivity gamma-ray spectrometer survey suitable for detailed exploration and mapping of an area. Appendix II lists some of the reasons why unsatisfactory airborne gamma radiation results have been obtained in the past.

6.3. High-sensitivity spectrometric surveys

The figures which follow demonstrate the advantages of comprehensive data presentation based on automatic data processing and show why gamma-ray spectrometry can be an effective uranium exploration tool. They are made up of profiles and maps obtained with the Geological Survey of Canada's high-sensitivity spectrometer system. All the examples shown are from data collected in the 1970 and 1971 seasons which have been released on open file. Figure 2 illustrates the aircraft used to collect this data. This machine was specially selected because of its good low- and slow-flying performance. Figure 3 illustrates the spectrometer equipment as used in 1971. A comparison with Fig. 9 of Darnley and co-workers [12] indicates the extent to which, over a 3-yr period, a reduction in size of modules has been accompanied by an increase in system complexity.

The profiles have all been computer plotted and follow a standard format, with the distance in statute miles from some arbitrary base line plotted from left to right. The irregularly spaced numbers are fiducial points. The integral (total radiation), potassium, uranium and thorium corrected counts per unit counting time are plotted, as are also the U : Th, U: K, Th: K ratios and the terrain clearance. The sample counting time was: integral 0.5 s, other channels 2.5 s. The nominal terrain clearance

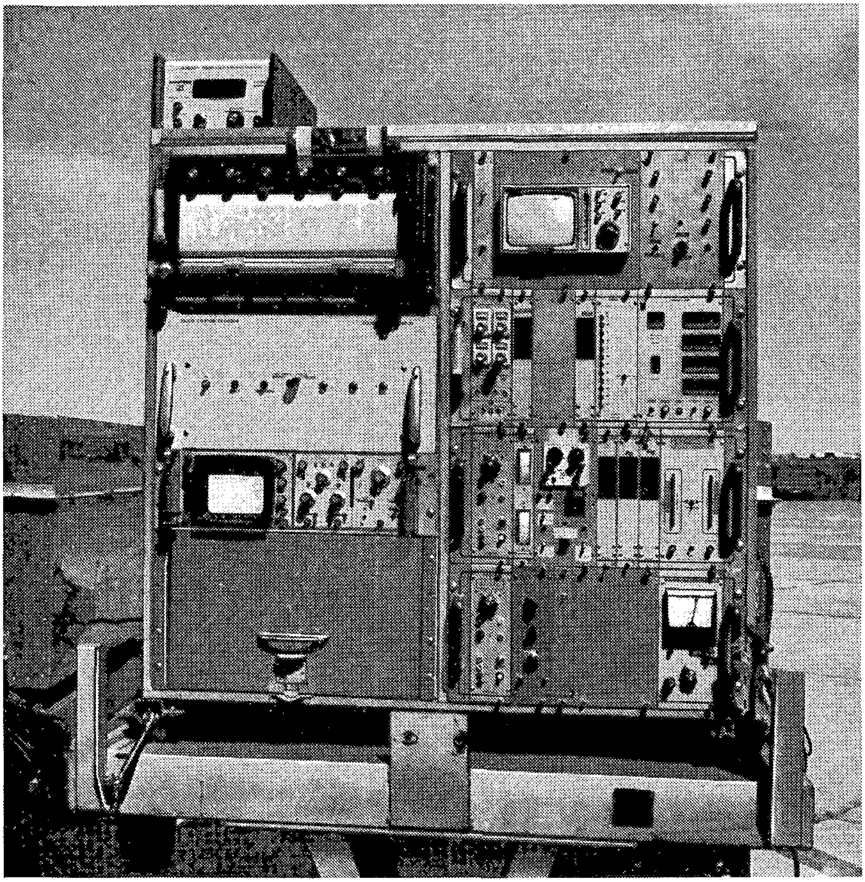

FIG. 3. The gamma-ray spectrometer equipment rack on a trolley waiting to be placed in the aircraft. The box on the left of the picture contains six of the twelve detector crystals. The equipment is as follows: left-hand side, commencing at top above rack, proton magnetometer control unit, six-channel strip chart recorder, digital tape recorder, spectrum display scope and video tape recorder; right-hand side, commencing at top, operator's wide-angle TV monitor for forward and downward viewing; next two layers include analogue computer for chart recorder, radar altimeter averaging unit, operator's input for coding magnetic tape, digital counters, 128-channel spectrometer encoder and power supplies.

for all these results, and the value to which they have been normalized, is 400 ft (123 m). All the profiles have been corrected for atmospheric background, Compton scattering, and (except Fig. 4) terrain clearance effects.

As a demonstration of the need to apply a terrain clearance correction, Fig. 4 shows results from a line to which no terrain clearance correction has been applied. Figure 5 shows the same line with the correction. The same raw data was used for the preparation of each plot. The ideal way to compare results is to superimpose the two records and the remarks which follow are based on such a comparison. This particular line in the

Elliot Lake area of Ontario is 40 miles in length and extends northwards from the town of Blind River. Maximum topographic relief in this vicinity is about 800 ft (250 m). Along this line the terrain clearance maintained by the survey aircraft varied between 200 - 800 ft. The height profile as plotted is a somewhat subdued mirror image of the topographic relief, because the aircraft is flown to follow surface contours. The height profile between the 29- and 40-mile marks shows several steep-sided ridges with narrow valleys between. The first point to note is the greater smoothness of the height-corrected results (Fig. 5) particularly the total and potassium measurements. The two anomalous features which stand out in Fig. 5 are near fiducials 1 and 3. The first of these is also prominent in Fig. 4 but the second is not. It is subordinate to a number of other anomalous features in the Fig. 4 presentation, especially those between fiducials 6 and 7 and 10 and 11. The anomaly near fiducial 3 is not prominent in Fig. 4 because it originates in a valley, so without height correction it does not stand out above the radiation from the higher ground to which the aircraft is closer. Conversely the apparent anomalies shown on Fig. 4 (between fiducials 6 and 7, and 10 and 11), especially noticeable in the total and potassium channels, are due to the fact that topographic ridges about 100 ft high are present at these points. Without a height-correction factor it is difficult to judge the extent to which the anomaly associated with the ridge in the vicinity of fiducial 1 is principally attributable to low terrain clearance over the ridge. A neighbouring ridge between fiducials 1 and 2 shows only a small associated build-up in count rate in the Fig. 4 presentation. After height correction, as demonstrated in Fig.5, the results confirm the unusually high thorium content of the ridge by fiducial 1. It should be noted in passing that neither uranium nor potassium show any marked increase at this point. The high concentration is attributable to heavy mineral bands in the Lorrain Quartzite. In summary, application of a height correlation removes topographic "noise" from the results and allows attention to be rapidly focused on areas of truly anomalous composition. The fact that the ratio values are not significantly affected by the presence, or absence, of a height correction is an indication that the attenuation factors being employed are valid.

Figure 6 is a line across the Mont Laurier area of Quebec (plotted on a different horizontal scale from the Elliot Lake lines) and shows the response obtained from a reported radioactive mineral-showing which occurs between fiducials 7 and 8. A prominent narrow uranium "spike" is accompanied by a distinctive "spike" in the U : Th and U : K ratios. Note that the uranium peak is displaced about 0.5 miles from the peak in the total radiation measurements. The latter peak is composed principally of thorium and potassium. This area contains relatively rugged terrain for the Canadian Shield and it should again be noted that without terrain correction the anomaly pattern would strongly reflect the ridge and valley distribution. A feature which is apparent on this particular plot, but which is not confined to it, is that the uranium count rate is occasionally registered as negative. The reason for this is the poor counting statistics of the net uranium count after the necessary atmospheric background and Compton scattering corrections have been applied.

Figure 7, which is also taken from the Mont Laurier area in Quebec, shows a prominent uranium peak close to fiducial 3 which would not be recognizable from the total radioactivity measurements. Its location on the

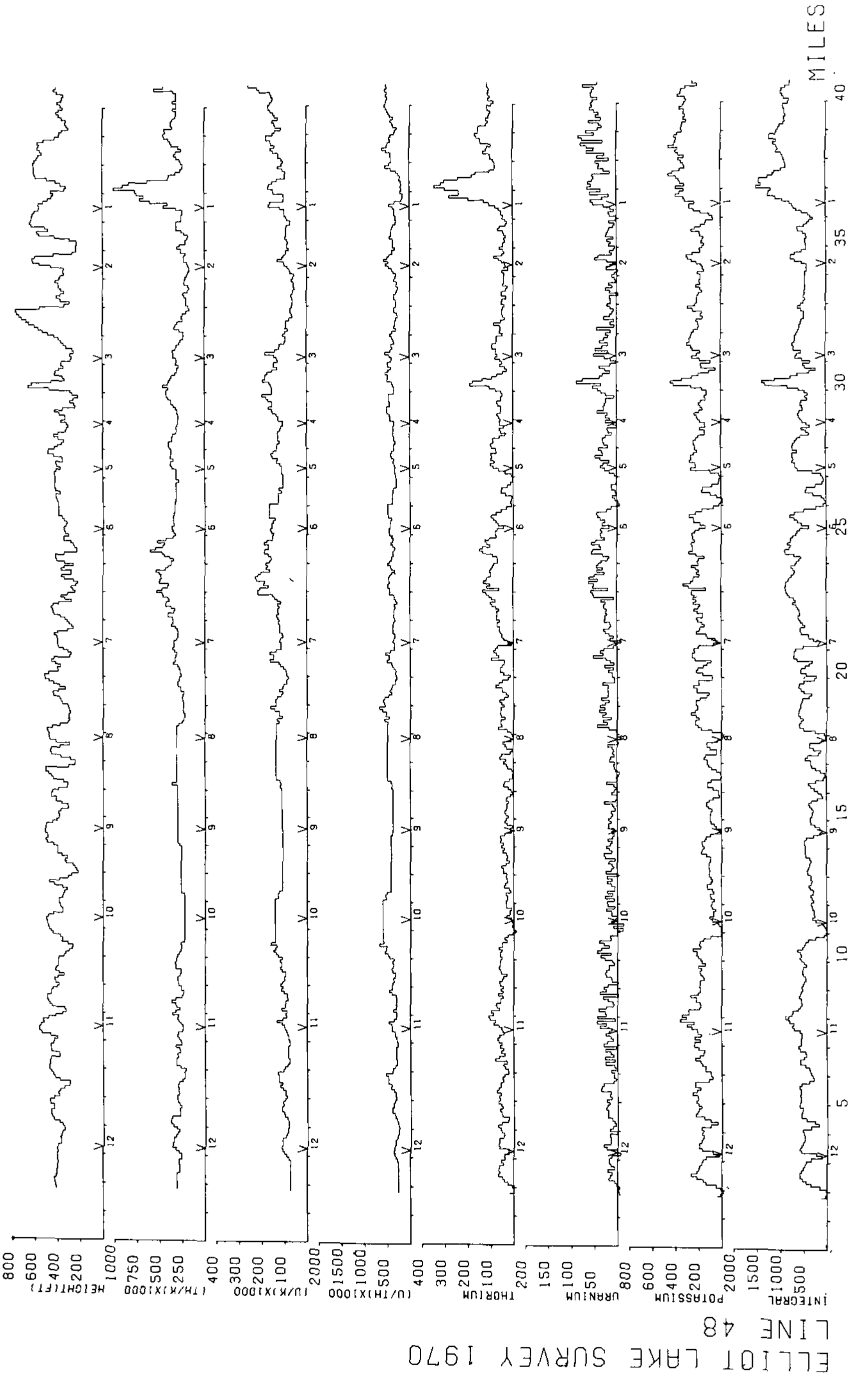

FIG. 4. Gamma-ray spectrometer profile. Elliot Lake Survey Line 48, without height correction.

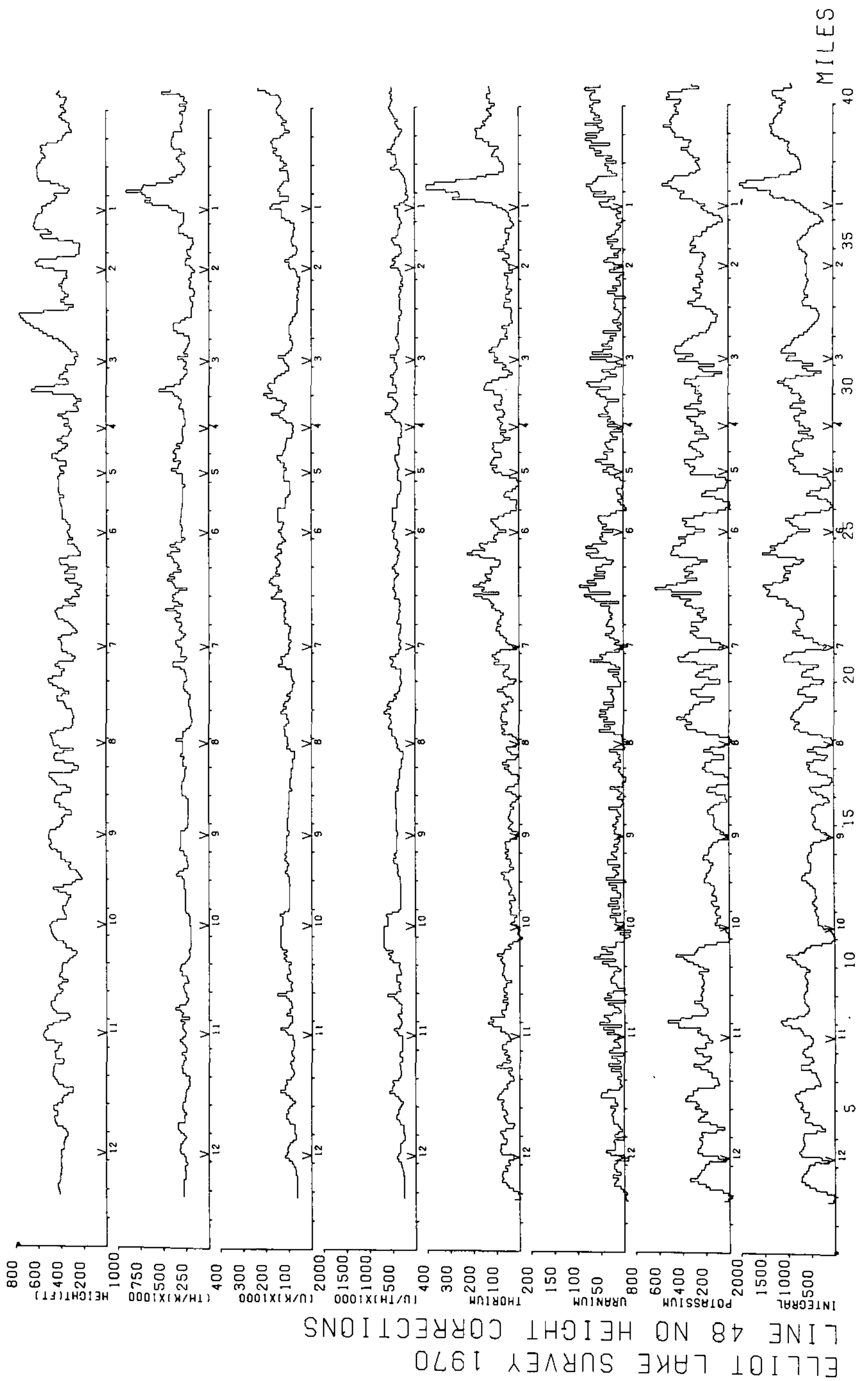

FIG. 5. Gamma-ray spectrometer profile. Elliot Lake Survey Line 48, with height correction.

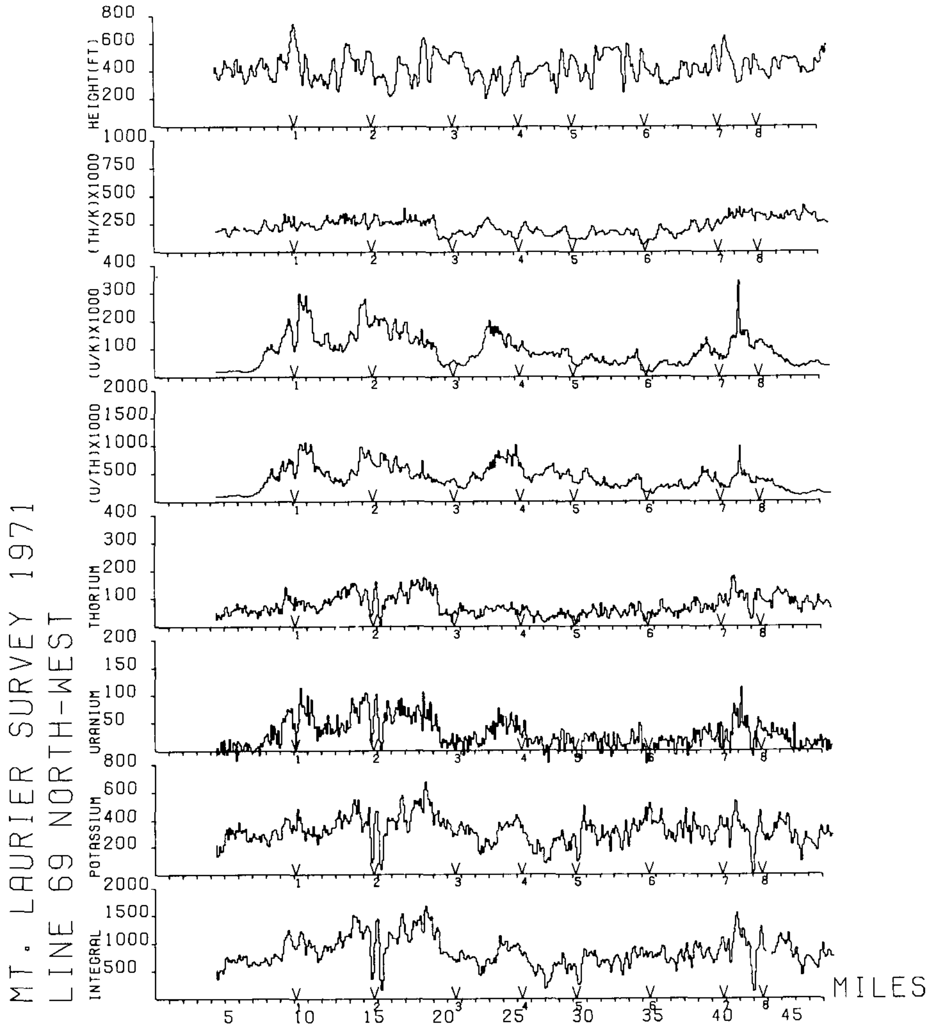

FIG. 6. Gamma-ray spectrometer profile. Mont Laurier Survey, Line 69. Example of anomaly provided by known radioactive mineral occurrence between fiducials 7 and 8.

flank of a broad regional radioactive "high", which is about 20 miles wide on this section, seems to be quite typical of many uranium occurrences encountered in the Canadian Shield. The uranium anomaly by fiducial 3 is associated with a prominent U:K ratio anomaly, but the U:Th ratio is not markedly anomalous at this point. The maximum U:Th ratio values observed on this line coincide with an area of low uranium and very low thorium content. This suggests that an uncommon rock type may be present there but this remains to be investigated.

Figure 8 is a line from the Fort Smith area of the Northwest Territories, which again illustrates the observed tendency for prominent uranium anomalies

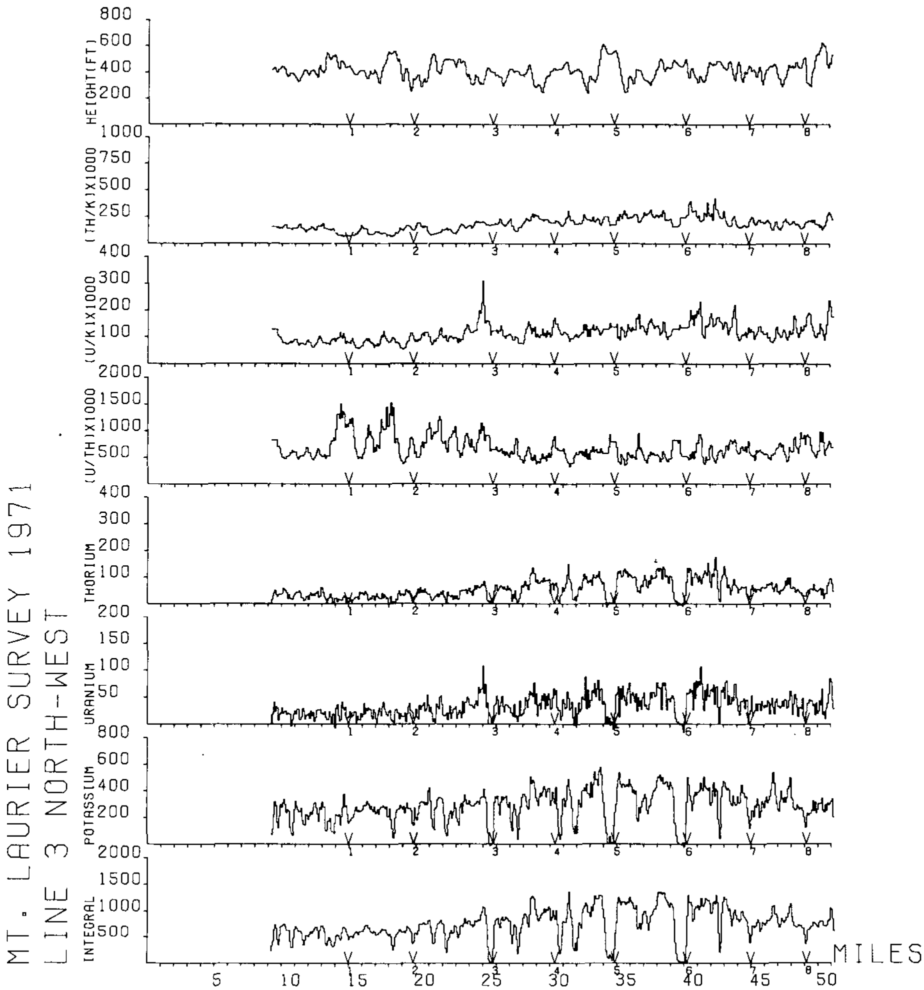

FIG. 7. Gamma-ray spectrometer profile. Mont Laurier Survey, Line 3. Example of uranium anomaly on flank of regional radioactive "high".

to be found on the margins of, or just outside, major regional radioactive highs. This high is about 28 miles wide on this section which is normal to the strike. The vertical scales on this plot are foreshortened relative to the other figures; despite this, the total and thorium count rates go "offscale" (although the original record, being digital, does of course record all values). The uranium maxima occur by the 31- and 60-mile marks. It is most unlikely that these would be found by any selection of anomalies based on a total count survey. Some of the earliest evaluation work with airborne radiation measuring equipment (Geiger and scintillation counters) was carried out in this area in 1949 and 1950, but the results were disappointing because the principal anomalies investigated on the ground were found to be due to granite of above-normal radioactivity, which was of no commercial interest.

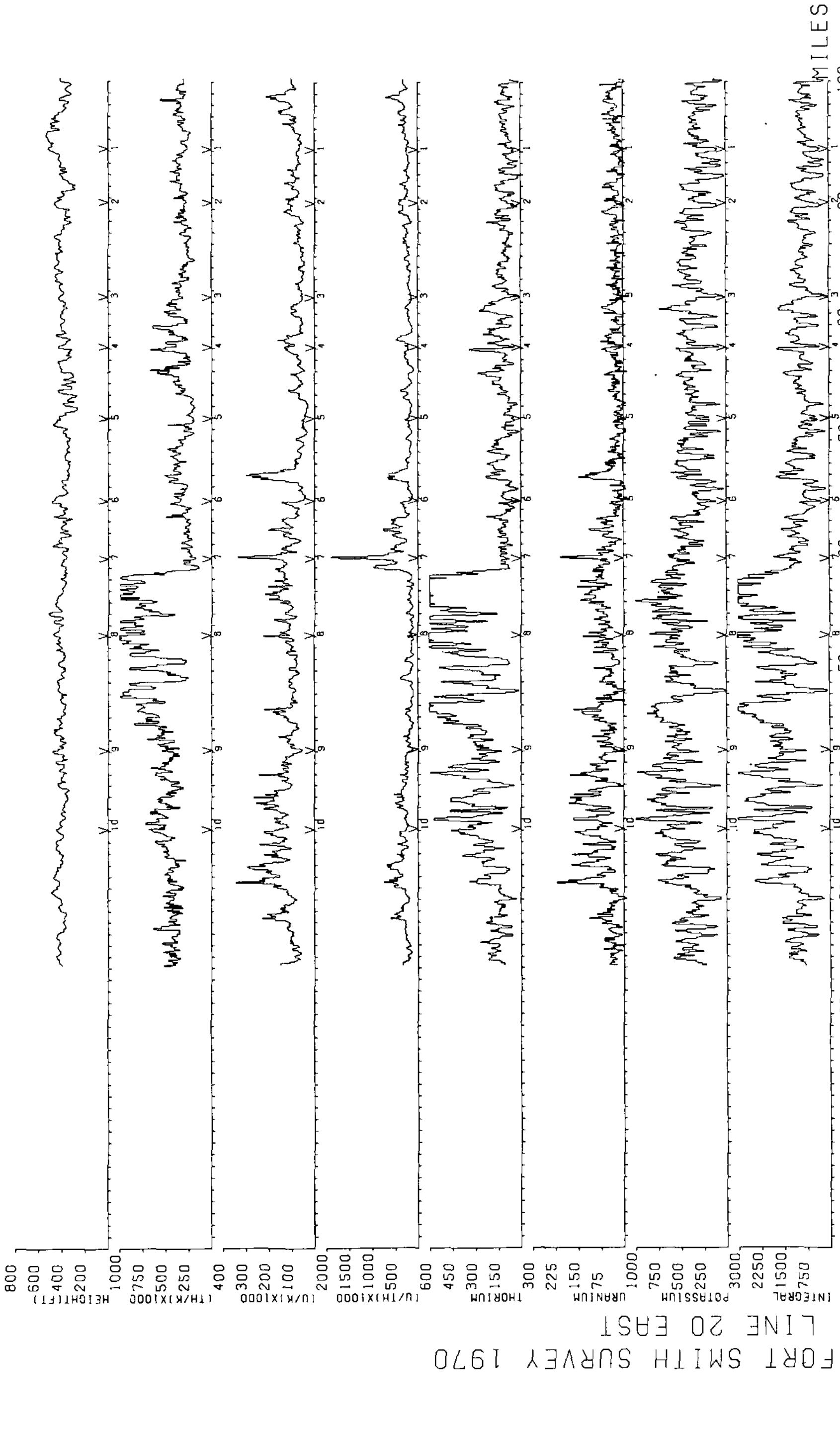

FIG. 8. Gamma-ray spectrometer profile. Fort Smith Survey Line 20. Uranium anomalies concentrated on margin of radioactive "high", which is dominated by high thorium content.

In the light of the results provided by gamma spectrometry it is now clear that the principal total count anomalies would generally be of this type because of the preponderance of thorium and potassium in the area.

Figure 9 is an isorad map of the total radiation distribution in the Fort Smith region, over an area of approximately 70×190 miles. The radiation level over much of this area is three times greater than the average level for the Canadian Shield. The problem of conducting a uranium exploration program in such a large anomalous area without the selectivity provided by spectrometry is readily apparent from this map.

Figure 10 shows the distribution of uranium within this same area. The average surface concentration within the shaded portions ranges from approximately 3 to greater than 6 ppm $\underline{e}$U (1 ppm $\underline{e}$U approximately equals 25 counts/2.5 s). This map also shows the numbers of flight lines and indicates their spacing, which was 5 km.

Figure 11 shows the distribution of U:Th values. From the point of view of economic potential the most promising localities are those where a high U:Th ratio coincides with a high uranium abundance. If attention is restricted to these localities then the area to be ground searched can be very substantially reduced.

Figure 11 shows that the distribution of high U:Th values seems to fall into a central north-south trend which is terminated to the north by an oblique northeast-southwest trend on the margin of the main high.

The highly anomalous radioactivity of the Fort Smith belt was recognized as such in the course of a cross-country reconnaissance flight with the GSC Skyvan system in 1969 [13]. The preliminary systematic airborne survey with its comparatively wide line spacing totalling about 5000 line miles was flown in a three-week period in 1970. This provided the information for the profiles and maps illustrated above. If on the basis of this information and the available ground information it was decided to pursue uranium exploration in this area, then the next logical step would be to fly selected portions with closer line spacing (down to a minimum of 0.25 miles) to define better the small zones for detailed ground investigations.

Other results on the GSC high-sensitivity gamma-ray spectrometry system have been published [1, 3, 13] and much more information on this work is also available through Geological Survey of Canada open file releases.

7. FUTURE DEVELOPMENTS

Future developments in the realm of airborne gamma-ray spectrometry can be considered in two categories: those which entail technological developments and those which only require elaboration of existing techniques.

The principal limiting factor in the current state of the art is the difficulty in obtaining sufficiently high count rates, together with adequate energy resolution. Plastic scintillators are now available which are relatively inexpensive, so that large detector volumes may be obtained to provide high count rates. Unfortunately the energy resolution of such phosphors is inferior to that of NaI(Tl), which has been the most widely used radiation detector since the inception of gamma-ray spectrometry in the early 1950s. Sodium iodide is far from ideal because a large volume is required to achieve even a modest count rate under operational conditions, as indicated in

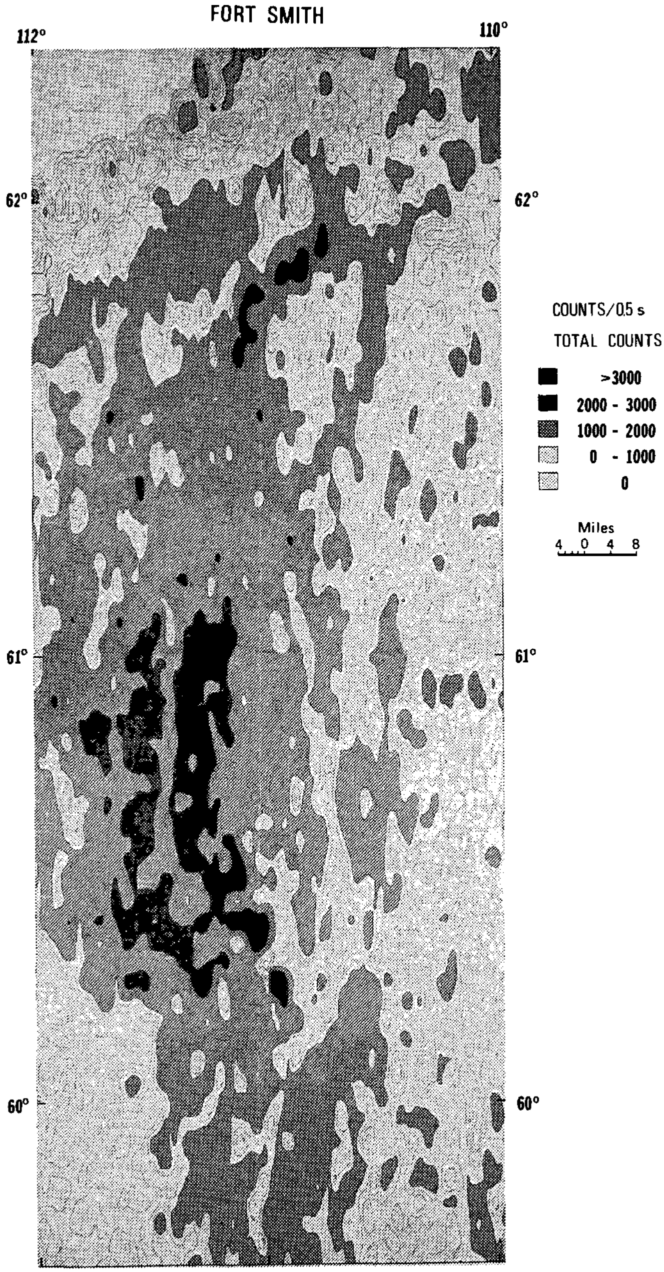

FIG. 9. Regional map of total radioactivity: Fort Smith area NWT and Northern Alberta. Zero count area is over Great Slave Lake.

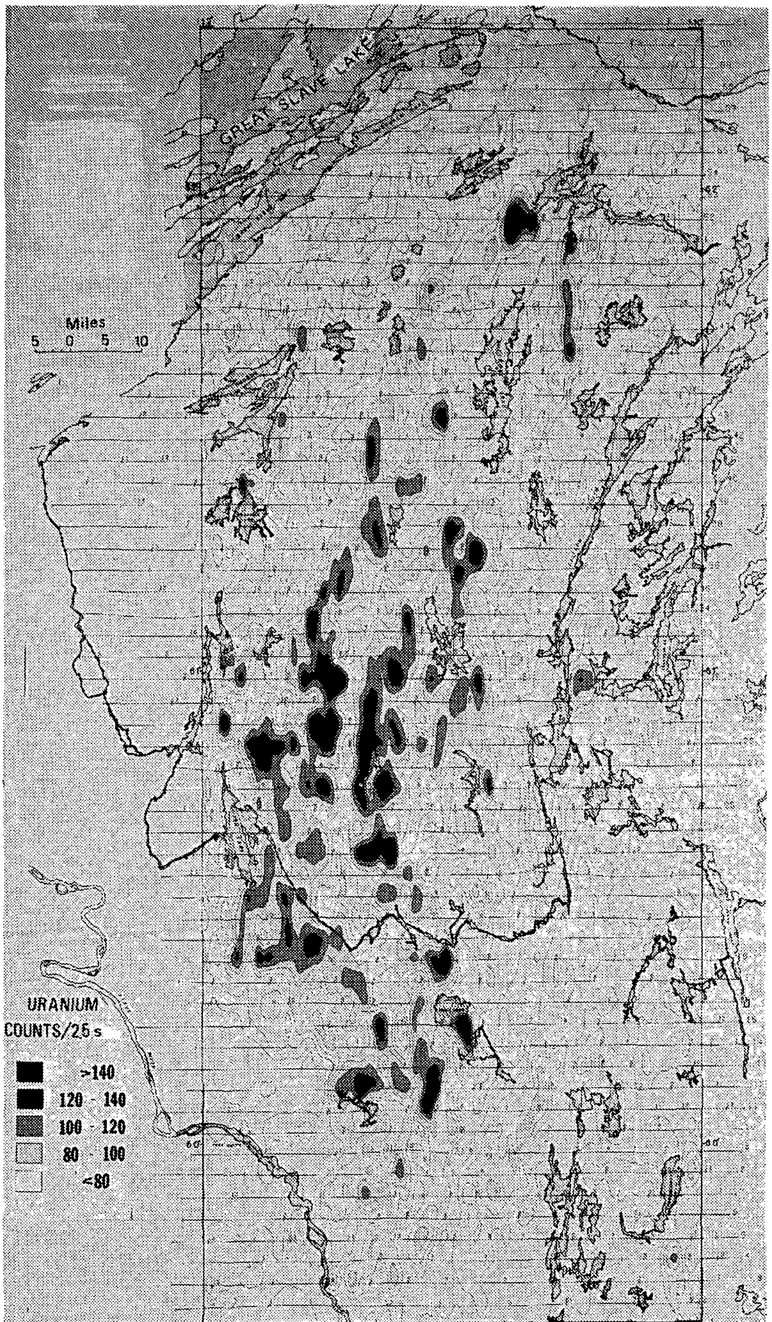

FIG. 10. Regional map of uranium content: Forth Smith area NWT and Northern Alberta. 25 counts/2.5 s $\simeq$ 1 ppm eU.

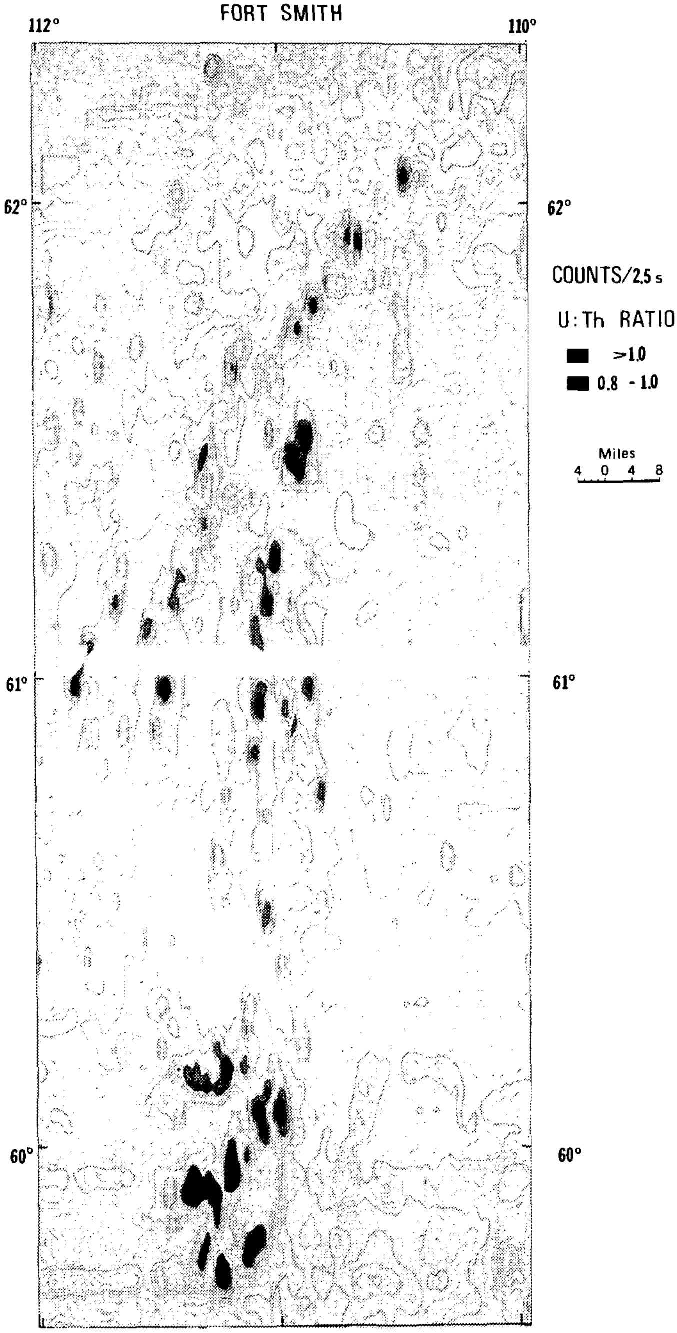

FIG. 11. Regional map of U: Th ratio variation: Fort Smith area NWT and Northern Alberta. Value plotted is ratio of count rates. A count rate ratio of 1 is approximately equivalent to an element abundance ratio of U: Th = 0.5. Crustal average is approximately 0.25.

Table VI, and the best energy resolution obtainable with a high-sensitivity system is about 12%. Although solid state detectors (Ge(Li)) have been available for several years, their high-resolution advantage is counter-balanced by their low specific count rate, need for cryogenic cooling, availability only in small sizes, tendency to premature failure and their high cost. The need to find a method of radiation detection which combines the advantages of and is also superior to NaI(Tl) and Ge(Li) is important from the point of view of economics as well as of scientific data quality. Sodium iodide detectors constitute about 60% of the cost of high-sensitivity airborne spectrometry equipment and constitute about 75% of the equipment weight and volume. Weight and volume dictate the size of aircraft required to fly a survey, which in turn is a significant factor in the overall cost. For example, the difference in operational cost between a light, single-engined aircraft (Cessna 180) and a medium twin-engined aircraft (DC 3) is approximately $1.25 per line kilometer in Canada. Any means of weight and volume reduction which does not result in impaired data quality therefore warrants close consideration. For this economic reason, airborne systems should always be made up with the most compact and light-weight subsystems available, subject of course to possession of the necessary performance and reliability. Multichannel analogue strip chart recorders have been notoriously bulky pieces of equipment ever since they were first adopted for airborne use, and a satisfactory light-weight unit remains to be perfected. A permanent in-flight analogue record of results is essential for data monitoring. As long as the costs of miniaturization do not escalate out of proportion, there will always be an advantage in using the most compact equipment, either to employ the smallest possible aircraft, or to increase the variety of equipment carried on an existing aircraft.

From both the theoretical and practical point of view it is advantageous to record the complete gamma radiation spectrum on magnetic tape if it can be achieved without the penalty of excessive equipment weight and the existence of an unacceptable dead-time whilst readout is taking place. The advantage provided by full spectral recording would be increased if detectors were available which were capable of better energy resolution than is now provided by sodium iodide. When technological developments have progressed sufficiently, this approach to airborne gamma-ray spectrometry will almost certainly become standard practice. This would provide a solution to several problems mentioned in the preceding sections, for example, it would enable one or more low-energy peaks in the uranium series spectrum, e.g. the 0.77-MeV peak, to be used to monitor atmospheric ^{214}Bi and provide a real-time correction for this background radiation; it would also facilitate the use of height-dependent Compton scattering corrections for "uranium".

Another technological development which would benefit high-sensitivity gamma-ray spectrometer surveys (and also all other types of airborne surveys with digital data recording) involves the perfection of a system of automatic track recovery capable of giving a point by point data position record with an accuracy of ±50 m along lines up to 50 km in length. Navigation systems which are adequate for normal air traffic operations do not possess sufficient accuracy for air survey work, especially when this has to be conducted at very low levels in turbulent conditions.

Insofar as the adoption of a standardized method of presenting gamma-ray spectrometry data in terms of element abundance is highly desirable, future developments will require the establishment of calibration ranges in

different countries. It is desirable that, in the future, corrections should be applied to data with respect to both air density and ground moisture content. The first is relatively easy to apply whilst the latter is more difficult to establish. The most satisfactory unit for standardizing total count radiation surveys will have to be established as rapidly as possible.

As part of the anticipated increasing use of high-sensitivity gamma-ray spectrometry as an aid to both geological mapping and mineral exploration, encouragement will have to be given to the systematic acquisition and documentation of case histories concerning airborne surveys and relevant ground investigations, to learn of their successes, weaknesses and failures and thereby seek methods of improving interpretation techniques.

Finally, future developments of airborne gamma-ray spectrometry will be only of limited value unless the results are integrated as fully as possible with all other sources of earth science information. No single method of airborne exploration warrants use in isolation if it is at all possible to measure other parameters simultaneously. Multisensor surveys will be used increasingly in the future. The main precaution to be observed with multisensor surveys is that one must be careful to optimize the operational parameters, to avoid situations where, in order to comply with some predetermined specification for one sensor, results from another (such as a gamma-ray spectrometer which is very sensitive to flight parameters) are of unsatisfactory quality. The output from multisensor surveys, especially gamma-ray spectrometer and magnetometer surveys, will be amenable to pattern recognition analysis and, when used in conjunction with airphoto interpretation, will provide a much more powerful tool for airborne geological mapping than now exists.

8. CONCLUSION

Airborne gamma radiation survey techniques provide an efficient means of exploring for new uranium deposits. In the interests of economy and maximum efficiency the following considerations should be kept in mind:

(a) Total radiation measuring systems are suitable for:

(1) Preliminary reconnaissance surveys to recognize broad areas requiring more detailed examination by airborne systems capable of energy discrimination.

(2) Target identification within areas where the mineralization controls are well known and the possibility of confusion with non-mineralization targets can be eliminated.

(b) Spectrometer systems should be used:

(1) Wherever ground access is difficult and there is the need to classify and select different types of radioactive anomaly prior to ground examination.

(2) Wherever significant showings may be very small or very diffuse at the surface and are recognizable only because of a small increase in the relative concentration of uranium.

(c) Comparable results may be obtained from different systems using different combinations of detector volume, height, speed and line spacing. However, costs may vary substantially.

(d) Any type of airborne radiometric system, and spectrometer systems in particular, must provide a sufficiently high count rate after all corrections have been applied to be statistically meaningful at the required sensitivity. The maximum number of counts per unit distance must be achieved. This is obtained by maximizing detector volume and minimizing airspeed.

(e) Data should be of sufficiently high standard to merit comprehensive presentation by automatic compilation methods.

(f) To standardize results between surveys, results should be expressed in terms of mean radioelement abundance at ground level.

(g) The most important parameters in uranium exploration are the U:Th and U:K ratios taken in conjunction with the uranium measurements.

APPENDIX I

SAMPLE SPECIFICATION FOR A HIGH-SENSITIVITY GAMMA-RAY SPECTROMETER SURVEY

Based on the Geological Survey of Canada,
Atomic Energy of Canada Ltd. Skyvan system

OPERATIONAL PARAMETERS

Mean flying height:	400 ft ± 25 ft
Local height deviations:	+400 ft, - 200 ft
Airspeed:	To be held ±5 miles/h in the range 60 - 120 miles/h. Detector size and counting interval to be determined according to speed of aircraft to be used. The contractor may select the type of aircraft to be used, but this will determine certain details of the equipment, especially detector volume.

DETECTOR SYSTEM

Crystal size:	Minimum diameter of individual crystals: 5 in. Minimum thickness of individual crystals: 4 in.
Detector volume:	The number of crystals employed must provide: a total of approximately 1500 in^3 of NaI(Tl) at 60 miles/h or approximately 3000 in^3 of NaI(Tl) at 120 miles/h or pro rata at intermediate speeds.
Detector stabilization:	Maintain at constant temperature and, if single channel analysers are used in the spectrometer system, a radioisotope calibration-source spectrum stabilizer is necessary. This calibration source must not interfere with the specified window widths.

SPECTROMETER SYSTEM

1. Spectrum analysis: (a) Preferred system: multichannel analyser with optional detector stabilization with windows corresponding to 1.36 → 1.56 MeV (^{40}K)
1.66 → 1.86 MeV (^{214}Bi)
2.42 → 2.82 MeV (^{208}Tl)
0.4 → 2.82 MeV (Σ)
with oscilloscope display of spectrum and window positions for calibration monitoring purposes.

(b) Alternative system: stabilized detector assembly with single channel analysers corresponding to above window widths.

The system is to be calibrated by setting up the spectrometer to provide three adjoining windows, each 50 keV wide, to bracket any one of several photopeaks of specified energy. For prime calibration ^{88}Y and ^{137}Cs are necessary; for routine calibration ^{40}K (from the natural environment) should be used.

Stability of the system to be demonstrated by:

(a) Drift in count rate over continuous 8-h test period to be less than ±2.5% of mean count rate without manual adjustment.

(b) Mean count rates from a natural radiation test source at a fixed distance to be reproducible within ±2.5% throughout survey operating time using a standard calibration procedure.

The Compton scattering corrections and sensitivity of the system in terms of count rate per unit concentration for each radioelement is to be established on the GSC test pads at Ottawa and by a test flight over a calibration strip.

2. Sampling time:	Counts to be accumulated over sampling times in the range 0.5 - 5.0 s; to be preselected according to operational requirements.
3. Terrain clearance:	A suitable means of continuously monitoring terrain clearance, e.g. a radar altimeter, must be used in conjunction with the spectrometer, and mean terrain clearance during each sampling period must be determined and recorded with the data from the spectrometer. The performance of the altimeter must be demonstrated to be satisfactory for the purpose. Unserviceableness of this instrument will render all results unacceptable.
4. Line spacing:	Detailed survey: 0.22 mile (or 0.5 km) Reconnaissance survey: 2.5 or 5.0 km; to be determined by scientist in charge.
5. Track recovery:	Automatic track recovery method of proven reliability under all normal survey conditions and/or TV/video tape recording and/or photographic strip film camera. Fiducial points must be entered on the magnetic tape record at the start and finish of every line, at least every 4 miles if an approved automatic track recovery system is employed, and at least every mile if reliance is placed solely on a track recovery camera.
6. Recording:	Digital recording of raw uncorrected data on magnetic tape is required. Contractor either to be responsible for provision of his own data recording, processing and presentation programs or he may use GSC gamma-spectrometry data reduction programs. In either case data must be in a standard format as recommended by GSC. In-flight analogue presentation of data is also necessary to monitor correct functioning of all parts of the system and make preliminary assessment of results whilst survey is in progress. There must be provision for operational information such as line number, date, time of day, type of measurement, and fiducial points to be recorded on the tape. There must be provision for in-flight or immediate post-flight verification of magnetic tape digital recording. An airborne or ground read-out/display unit is mandatory.

DATA CORRECTION

Raw data must be corrected as follows:

1. For background (cosmic and atmospheric) radioactivity. This must be determined at the beginning and end of flight by flying an approved test line which is at least 3 miles long.
2. For deviation from mean terrain clearance, using the recommended formula.
3. For Compton scattering contributions to the observed ^{40}K and ^{214}Bi count rates. Correction factors must be confirmed by making observations on the GSC calibration pads, Uplands Airport, Ottawa.

DATA PRESENTATION

Data must be presented in the following forms:

1. Digital printout in tabular array of raw data (computer listing).
2. Profile for each line flown to show terrain clearance, integral, potassium, uranium and thorium count rates and the ratios of the U:Th, Th:K, U:K count rates plotted against distance along the line. Fiducials to be shown superimposed on the distance axis.
3. Plots of flight lines superimposed on base map of the area to show exact location of fiducial points.
4. Contour maps to be prepared for each of the parameters shown in profile form at a scale to be confirmed. Contour interval to be specified following production of profile.
5. N. B. The programs to be used, provided by the contractor, must be of equivalent quality to programs developed by GSC. The right is reserved to require the contractor to demonstrate the accuracy of his computer programs by satisfactorily reducing test data provided by the Geological Survey of Canada.

Note: This draft specification is for general information only. Details of the digital tape format and data reduction programs can be discussed on request.

APPENDIX II

COMMON CAUSES OF UNSATISFACTORY AIRBORNE RADIOMETRIC SURVEYS

1. Installation close to radium-luminized equipment causing excessive background values.
2. Shielding of detectors by aircraft fuel tanks causing reduced sensitivity when tanks are full.

3. Intermittent electronic noise causing spurious anomalies.
4. Inadvertent or erroneous setting of high-voltage supply, window widths or energy thresholds.
5. Improperly adjusted base lines on analogue records.
6. Binary bits missing or added in digital recording.
7. Unreliable radar altimeter.
8. Failure to monitor atmospheric background and fly test line.

ACKNOWLEDGEMENTS

This review of airborne gamma radiation survey techniques has been made possible by the efforts of many individuals over a five-year period during the development of the Geological Survey of Canada's airborne, ground and laboratory gamma spectrometry projects. Credit is due to all who have participated. Especial acknowledgement is due to Dr. R. L. Grasty for the development and application of the computer routines for automatic data presentation and for helpful discussions on the subject of Compton scattering and height corrections.

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DISCUSSION

J.F. DAVIS: We have had, from a practical standpoint, reasonably good success with quite a small crystal volume in the spectrometer surveys. I am certain that the quantitative aspects of this are not so good, but I was wondering what your comment might be on the use of crystals of say less than 1000 cm^3.

A.G. DARNLEY: For Canadian conditions that would be a very insensitive system, but I think that if you are working in a specific area, then the prudent thing to do is to establish the general level of ground radioactivity likely to be encountered in the vicinity of potential targets. This assumes you know something about the nature of your target. Obviously in an area with a lot of exposure, and where the radioelement content of the rocks is high to begin with, the need for high count rate systems is reduced. Even so, to be sure you are not missing weak targets, it is unwise to rely on such a small detector volume unless it is to be flown very low and very slowly. What matters are the counts per unit distance, not the detector volume. If you are prepared to wait long enough in a particular spot, then you can maximize sensitivity.

S.H.U. BOWIE (Chairman): You want a helicopter really.

L. LØVBORG: I think that Mr. Darnley's proposal for a new unit for expressing the total count rate is a very good one. But I think that it is physically more relevant to refer to the radiation intensity from an infinite medium containing the average crustal abundances of uranium, thorium and potassium, rather than to base a new unit on potassium alone. A good name for this intensity would be one gamma, but unfortunately this name has been used in magnetic surveying. I think that one should consider the physical reasons when deciding on a new unit.

H.H. ADLER: I think I saw in your next to the last slide that the U:Th ratio was quite high and indicated an anomaly some distance from the Wollaston Lake deposit. However, in looking at the uranium and the thorium values, it seemed to me that that ratio was a result of a diminution in the thorium content rather than anything unusual in the uranium content. If I am correct in this, how would you use this in connection with evaluating that anomaly in terms of its nearness to the Wollaston Lake area? Can the diminution of thorium in this case, or the loss of thorium if one wants to put it that way, be of any value?

A.G. DARNLEY: The use of ratios as a means of focusing attention on certain points is far from foolproof. I think it is the principle indicator provided by the method, and there is no doubt that you obviously can obtain

a high U:Th ratio, as you say, through a deficiency of thorium. It is a rather unusual situation nevertheless. We have found during the course of our own ground investigations in the Northwest Territories one particular place where we appear to have very favourable U:Th ratios and where the uranium is not particularly high but the thorium is very surprisingly low, and this is in a narrow belt of silicic gneisses. We do not know the reason for this; it is something that calls for detailed investigations. Based on present knowledge, there is no indication there of any uranium mineralization, but nevertheless, and I can say this quite categorically, it is unusual to get this sort of thing. Any such situation deserves investigation. If you are in an area where you know that some of your U:Th ratios are significant and you find a ratio anomaly along the strike where uranium does not go up but thorium goes down, you should consider the possibility that perhaps there is only a very limited amount of outcrop in that particular sample area. It may be a genuine indication of there being some relative enrichment in the ground even though, in terms of the absolute uranium abundance, it may not seem significant. You must always use geological judgment in the evaluation of these things.

D. OSTLE: I think that one of the most interesting statements that Mr. Darnley made in the course of the presentation of his paper was that uranium deposits are in general associated with, or found in, regions of high radioactivity and he pointed to the attraction of flying total gamma surveys at very wide intervals in order to detect such zones. This must be an attractive proposition for many of us here if the validity of this is high. Could Mr. Darnley explain his definition of a high radioactivity area? Does this high level of radioactivity transcend the variations within the different rock components? Obviously, one will find high radioactivity in a black shale facies for instance. Would that form a basis for encouragement in prospecting, or would there be an overall enrichment of black shale and everything else within an area? Could he enlarge a little on this definition of what constitutes a high radioactivity area.

A.G. DARNLEY: The basis for this observation stems from our own work and from the literature. Areas where we have shown this to our own satisfaction include Bancroft, Elliot Lake, Uranium City, Wollaston Lake and the Mont Laurier region in Quebec. A cursory examination of the literature indicates that southwest England would show similar characteristics. I suspect Sutherland in Scotland would perhaps be regionally anomalous as well. I understand there are anomalous features on a regional scale in northern Australia. These features have a minimum strike length of the order of tens of kilometres, with a minimum strike width of the order of several kilometres. The cross-country spectrometry flights which we flew in Canada in 1969, from Ottawa to Yellowknife — a distance of about 2500 miles — show that over a substantial portion of the Superior province of the Shield there is a relatively constant level of radioactivity with minor perturbations within it. These variations can be related to granites, areas of basic rock and so on. Superimposed upon this base level there are a few local zones, where there is perhaps a factor of 2 increase in radioactivity over a distance of a few tens of miles. The radioelement enrichment within these highs in the Superior province is not as great as within the Churchill or the Slave provinces of the Shield. There seem to be small variations relating to the details of the geology, and superimposed upon this over a relatively small proportion of the total area are regionally prominent features.

As far as we have determined, and much more ground and laboratory work needs to be done, most of the rock types within these zones show an above-average level of radioactivity, but of course, the different rock types within these zones vary between themselves. The economic uranium occurrences are commonly on the fringes, but may be within these zones. Incidentally, I would very much like to have more information as to the level of radioactivity of the granitic areas in the Western USA for those areas which may be significant as sources for the sedimentary uranium. There are some extremely high areas of radioactivity along the western edge of the Canadian Shield and I wonder just exactly what there might be under the northern extension of the Prairies, in the area to the west of and between Lake Athabaska, Great Slave Lake and Great Bear Lake. There is not much to be seen on the surface, but there could be all sorts of things underneath.

S. H. U. BOWIE: Thank you, Mr. Darnley. I would just like to make one comment on the association of uranium with high-activity areas. I do not know whether it is a world-wide phenomenon or not. I do think we need a lot more information on this, but it is certainly true to say that uranium, thorium and potassium are all lithophile elements, that tend to occur together; they also tend to be associated with acid igneous rocks rather than basic igneous rocks. However, we know of plenty of granites, of large areas of granitic rock which are highly anomalous and contain amounts of uranium well beyond the clarke and yet these have no known associated uranium deposits. I refer to the Conway granite of New Hampshire and the Kaffo granite of Nigeria as typical examples. I believe we have to be a little bit careful in how we extrapolate the type of observation Mr. Darnley has made.

A PRACTICAL APPROACH TO URANIUM EXPLORATION DRILLING FROM RECONNAISSANCE TO RESERVES

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Abstract

A PRACTICAL APPROACH TO URANIUM EXPLORATION DRILLING FROM RECONNAISSANCE TO RESERVES.

The use of the drill rig early in uranium exploration, assisted by sophisticated geochemical and geophysical techniques, has led to a relatively unusual mineral exploration procedure. The drill is used in sedimentary-type uranium exploration to provide not only mineralization information, but stratigraphic, alteration, and other data that is not evidenced by surface expression. Portable drill rigs capable of drilling over 600 m per shift permit a total exploration cost of less than $10/m. In the United States of America this type of exploration, guided primarily by continuing geological analysis, has led to the discovery of large amounts of uranium at a cost of less than $2/kg. The use of conceptual models based on known districts and the geochemical characteristics of uranium provide the framework for the initial exploration phase. The exploration techniques of a drilling program require emphasis on careful, but not unnecessarily detailed, geological analysis. The size and grade of a minimum necessary target can govern the detail required as well as the exploration budget.

1. INTRODUCTION

In the United States of America, geological knowledge gained from the development of large uranium reserves in sandstone-type deposits, increased understanding of geochemical and sedimentary controls, low drilling costs and advanced logging techniques have led to the use of a relatively unusual combination of mineral exploration procedures. Guided by proven concepts, and hampered by the lack of meaningful surface evidence, the drill rig has emerged as the primary means of providing access to data in all phases of exploration, from early reconnaissance to the final outlining of an ore body. With proper geological guidance, the drill hole and its samples provides stratigraphic, lithologic, structural, alteration and geochemical data that is unattainable by any other means. Use of the rotary non-core drill in the early stages of exploration can eliminate much of the uncertain theorizing based on meager evidence, thus permitting rapid and relatively definitive evaluation of a potential area.

Most US exploration companies allocate at least 40% of their budget for direct drilling costs. An active firm will drill over 100 000 m, and some firms as much as 500 000 m, during a year. During the peak exploration year, 1969, US exploration firms drilled over 9 000 000 m.

Using logistics similar to those encountered in the US, a drilling program would cost in the range of $3/m-$13/m — including all field, office, and overhead charges. A typical situation would be $7/m for holes averaging 150 m deep. In this case the first-phase drilling program might cost less than $50 000 for a basin covering 2500 km^2.

In addition to aiding uranium exploration, uniform and complete logging of drilling samples, together with the resistivity-gamma log, provide information which is valuable for evaluation of other mineral potential, water resources, and structural data for petroleum exploration.

Papers presented during the Agency's 1970 Panel on Uranium Exploration Geology discussed many potential uranium areas throughout the world. Subsurface exploration, in conjunction with various other exploration methods being discussed at this Panel, can convert much of this potential into uranium reserves. In the United States, extensive use of drilling in all phases of exploration has been paramount in the addition of large reserves at a cost of less than $2/kg.

2. PHILOSOPHY

During the initial phases of exploration, drilling is not performed for the express purpose of intersecting mineralization, but to enable the geologist to establish the geological framework that might lead to an eventual ore discovery. Indeed, the size ratio of a potential region to a typical mineralized area is so great that a large drilling program might well fail without an adequate geological study.

The large size of most potential sedimentary uranium areas precludes the use of saturation drilling even when considering the low cost per foot. Unfortunately many drilling programs degenerate into an inadequate attempt at saturation grid exploration because of an undisciplined exploration effort. On the other hand, a geologically oriented drilling program provides a relatively inexpensive and definitive means of rapidly evaluating large areas. Although some subjectivity in collecting data is important, the program must be set up with an understanding of certain genetic concepts regarding mineralizing solutions, source, geological structures and nature of the host rocks. In sedimentary uranium deposits, local controls and surface evidence are often obscure or complex, whereas regional controls are more definable. Because of this, the overall picture should always be kept in mind, and the program must never become bogged down in detail.

Data must be gathered in a systematic way, utilizing standardized forms, maps, and representation. Frequent staff reviews of the program, concepts, and techniques will help stimulate ideas and thorough data collecting.

The drilling programs must be scheduled to allow the geologists ample time to collect and analyse the data during the course of the field work. In addition to "<u>inter</u>-correlation" of drill hole geology, there must also be an "<u>intra</u>-correlation" with other geophysical, geochemical, and geological evidence.

By superimposing some hypothetical exploration efforts on a real district, the Gas Hills of Wyoming, one can see the possible results of a non-geological saturation program versus a geological effort. In the former, a grid of drill holes on one-mile centers (1.6 km) would have encountered no ore and little, if any, mineralization. This 128-hole effort would have cost over $100 000.

On the other hand, an interpretation of the stratigraphic, lithologic, and alteration data collected from the 28 holes drilled on two mile centers would have generally outlined the alteration patterns relating to the main ore trends of the Gas Hills (Fig. 1) and led the way to significant discoveries in the next

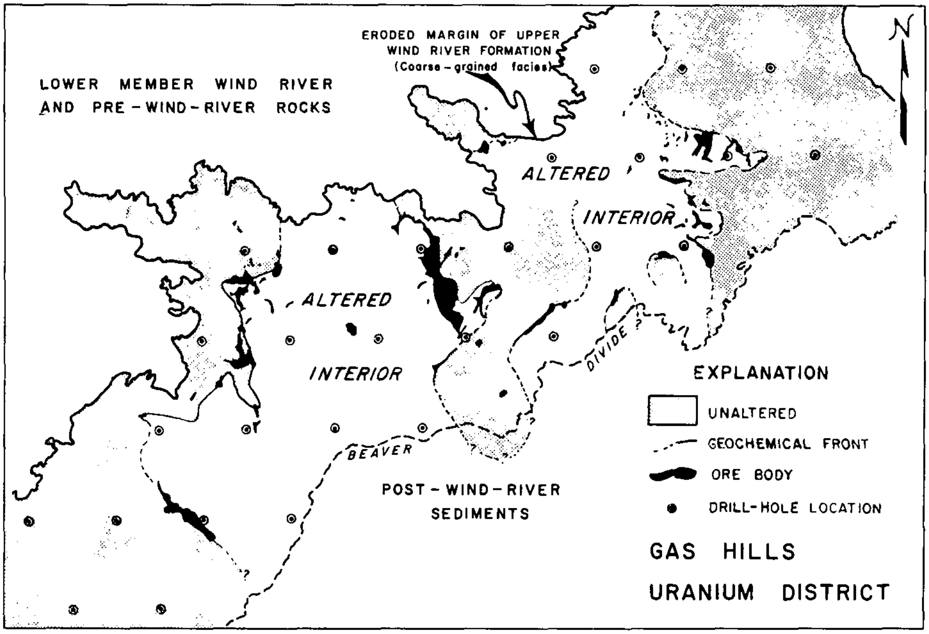

FIG. 1. The Gas Hills District showing ore distribution and the use of drill-hole data to establish potential reserves.

phase. The Gas Hills is estimated to have a cumulative reserve of over 45 000 000 kg U_3O_8.

The problem of discovery may be greatly magnified and complicated in other potential sedimentary areas where the area may be as large as 10 000 km^2. It is nice to have a good ore hole early in exploration, but an understanding of the odds will help avoid premature disillusionment and emphasize the absolute necessity for the thorough geological approach.

3. CRITERIA

The world's sedimentary sandstone-type uranium deposits exhibit many similarities which can be put together in occurrence models that are useful as a framework for analysis of exploration strategy and data. The necessary combination of broad features which provide source and control solutions, and the more local controls which affect ore emplacement, encourage a phased program that selectively eliminates large areas through examination of progressively more detailed evidence. For the most part, direct evidence of the important conditions is obtainable only by drilling.

A study of nine sandstone-type districts [1], representing over 300 000 tons U_3O_8, reveals many basic similarities. Of the reserves involved, 99% are influenced by intracratonic basins of the Cordilleran Foreland belt. Only the deposits in Texas are in a geosyncline. Virtually all of the deposits are in Mesazoic or Cenezoic formations. Granitic rocks

provide a major source of the host rocks, with areas of sandstone and shale also important. Ninety percent of the ores are in fluvial braided stream, alluvial fan, or flood plain deposits of arkosic or feldspathic sandstone. Quartzose sands are dominant in four districts. Tuffaceous sediments are present in the section above the host sandstone in every case – a possible source of carbonate solutions or uranium and a unique guidepost.

The dominant local feature is medium-to-coarse, poorly sorted sand with interbedded siltstones. The sand-silt ratios range from 1:1 to 4:1. All of the districts contain visible reducing agents such as carbonaceous debris. Prevalent secondary effects are alteration of the host rocks near the mineralized areas, pyrite within the unoxidized host rocks and oxidized uranium minerals in the outcrop. Groundwater anomalies in most of the districts indicate the importance of water sampling.

Beginning with the broadest features, the major categories for consideraation in a phased exploration program are:

(a) Province and source: a province is defined as a broad and generally indefinably bounded area in which uranium occurrences or uranium-rich rocks are relatively abundant. These may be radioactive granite or tuffaceous sediments. Unfortunately the source of uranium is usually unclear and even after much study is the subject of debate. Within a province, the explorationist should be initially concerned with the location of favourable host rocks.

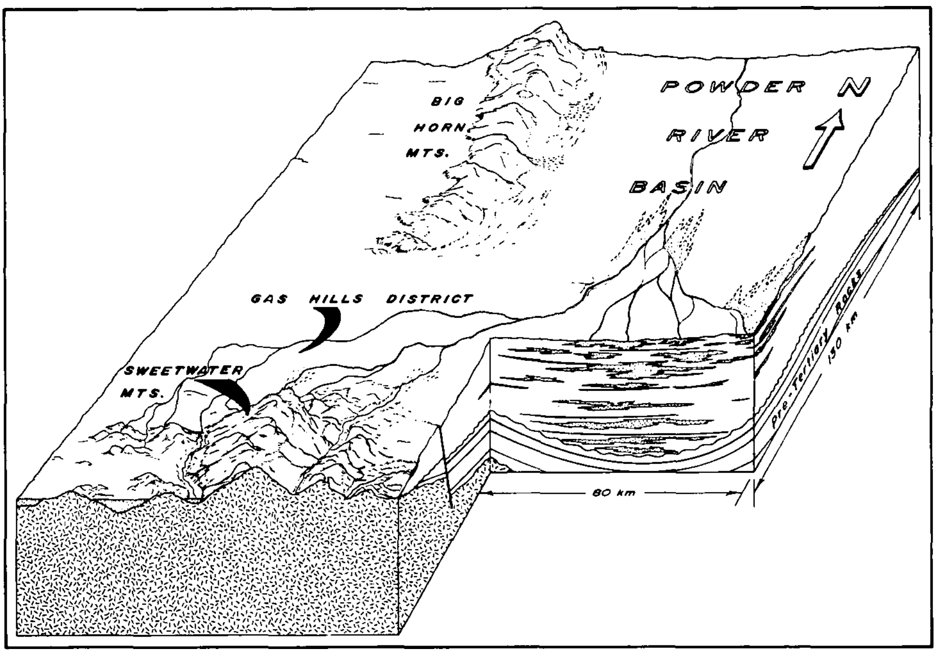

FIG. 2. A portion of the Powder River Basin, Wyoming showing development of Eocene sediments.

(b) Regional controls: continental fluvial sediments, and, to a lesser extent, marine deltaic or lagoonal sandstones, seem to provide the necessary regional transmissibility for solution movement, and also the environment for ore emplacement. An understanding of stream deposit characteristics is important in outlining a favourable area with widely spaced drill holes (Fig. 2).

(c) Secondary effects of ore solutions: a study of the solution conduits, i. e. the more permeable, thicker portions of the stream deposits, usually reveals geochemical tracks if uranium-bearing solutions have passed through. These effects may range from a readily distinguishable hematite or limonite stain to less evident enrichment of pyrite by metallic ions such as selenium, copper, molybdenum, and nickel. Trace amounts of uranium sometimes occur as thin "tails" at the top and bottom of the sand. Also, the solutions often have a destructive effect on certain mineral grains of the rock. Feldspars may be argillized and the ferromagnesium minerals are usually completely destroyed.

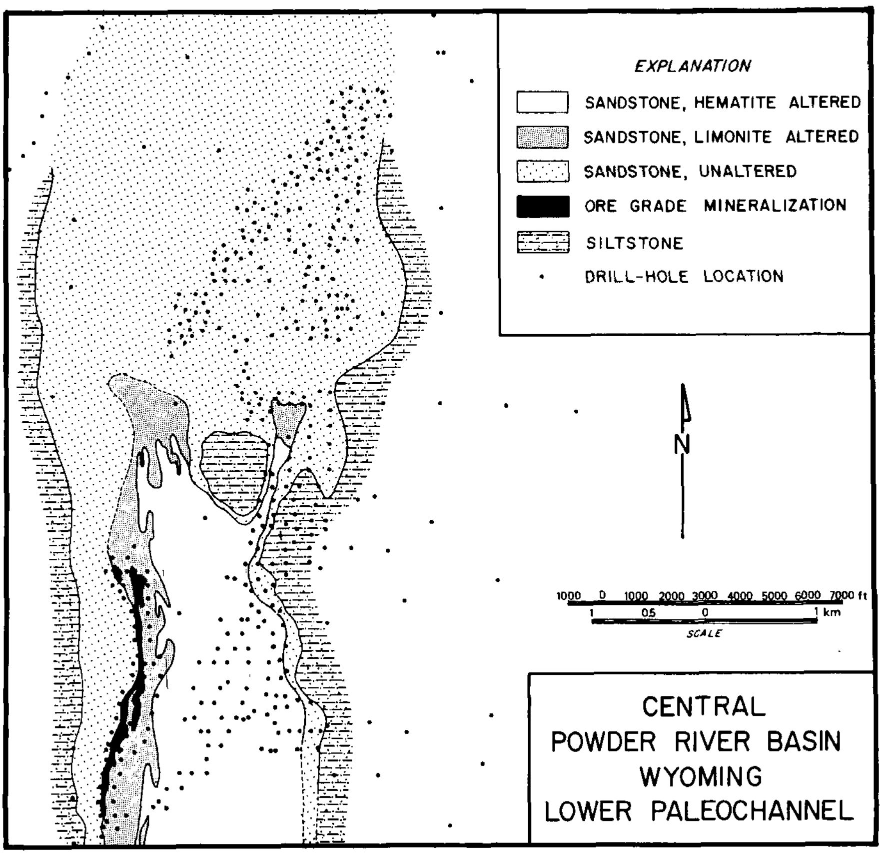

FIG. 3. Stratigraphic, alteration and mineralization map of a portion on one paleochannel.

(d) District controls: normally a marginal stratigraphic environment which acts as a physical control for the solutions and provides areas of reductants, i. e. vegetal organics and carbonaceous shales.

(e) Local ore controls and effects: in the case of "blanket" or "roll" deposits many features influence ore emplacement and yet the presence of these apparent controls does not always produce an ore body. Size or grade may be inadequate or there may be no mineralization at all. Rather than attempt to isolate all necessary specifics, initial district exploration might best be trend (alteration contact) exploration guided by minimum target size and those general geological criteria which favour mineralization. An analysis of several districts reveals that the presence of organic material, as well as stratigraphic location, sand thickness, sand-silt ratio and alteration type (Fig. 3) are a few of the more identifiable criteria. Major reserves in the Ambrosia Lake area are in "stack" deposits along fault and fracture zones.

(f) A major consideration is the minimum size and economics of the desired uranium reserves. This factor becomes progressively important with each phase of exploration. Indisputably, the most difficult decision is terminating exploration at the proper point.

4. EXPLORATION PHASES

Exploration prior to drilling usually includes a study of available geological data and preliminary mapping. Airborne gamma spectrometer surveys, soil and hydrogeochemical sampling, radon testing and other geophysical methods provide additional favourability data and assist in laying out the initial drilling plan.

Exploration drilling is phased to progressively evaluate controls, effects and mineralization as outlined in Section 3.

The preliminary drilling program is undertaken to assess the regional favourability of an area — essentially the definition and general location of possible host rocks. The drill holes are generally very wide spaced (10 to 15 km) and penetrate to sufficient depths to pass through the likely formations of interest and provide structural data.

After the existence of favourable-type rocks has been determined, drilling proceeds to search for, and define, portions of the area which have been affected by the passage of mineralizing solutions. Greater stratigraphic detail is also provided by the closer-spaced (2 to 5 km) drill holes of this phase.

A combination of favourable host rocks and secondary alteration, together with geochemical and geophysical indications, and possibly some mineralization, calls for preliminary trend or district exploration to establish the most apparent areas of favourability. "Fences" or relatively close-spaced holes (100 to 200 m) on lines at intervals of 1 to 2 km along the general area of the trend provide rapid delineation of favourable areas. Mineralization may only be present on portions of the altered or favourable trend, and ore might exist on a minute percent of the trend.

Before beginning detailed exploration of mineralized areas, the overall size and characteristics of the district should be assessed. The latter may

require several very close-spaced holes (10 to 50 m) to determine general size and grade parameters. Size, grade, and depth as related to operational economics should have a bearing on the final drill hole spacing and depth. Drilling in this phase may range from 10-m spacing on lines 30 m apart, to a grid of 100 m.

5. EXPLORATION TECHNIQUES

The rotary non-core drill hole provides inexpensive access to large thicknesses of rock for measurement of detail which can be analysed and mapped into a regional geological picture or for more specific evaluation of alteration and mineralization. The major items in this data collecting and analysis are:

(a) Drilling: responsible for good lithologic samples and a properly conditioned hole which will stay open for geophysical logging. The driller also provides observations regarding rock hardness and other conditions.

(b) Sample description: logged by the geologist as to rock type, colour, mineralogical characteristics, grain size and shapes, and alteration effects. Samples are often saved for more detailed examination under the binocular microscope, or for geochemical analysis.

(c) Geophysical logging: primarily radiometric and resistivity measurements performed immediately after completion of each hole. Mobile equipment must include quality electronics, be properly calibrated, and operated by trained personnel using standard procedures.

(d) Representation, analysis and correlation: standard colour and grain-size charts, specific forms and methods, and systematic maps permit better analysis and cooperation within the exploration group. Detailed geological data is most useful when combined into isopach and alteration maps, sections correlating lithology, alteration, and mineralogy, or charts and statistical analyses which illustrate the otherwise indistinct overall picture.

5.1. Drilling

Drilling equipment used in uranium exploration has evolved from the truck-mounted drill designed originally for seismic work in oil exploration (see Fig. 4). The main attributes of this type of rig are rapid portability under its own power; versatility — the same rig can plug- or core-drill with fluid mediums or air, and use fast-cutting drag bits, hard-cutting rock bits, or a down-the-hole hammer in extremely tough rock. Under most conditions, a two- or three-man crew can perform the drilling, water hauling, and mechanical tasks. Most of the units in service are capable of drilling to 300 m, with many in the field designed to penetrate to a depth of 600 m. Hole diameters range from 10 to 20 cm — 12 being the most common.

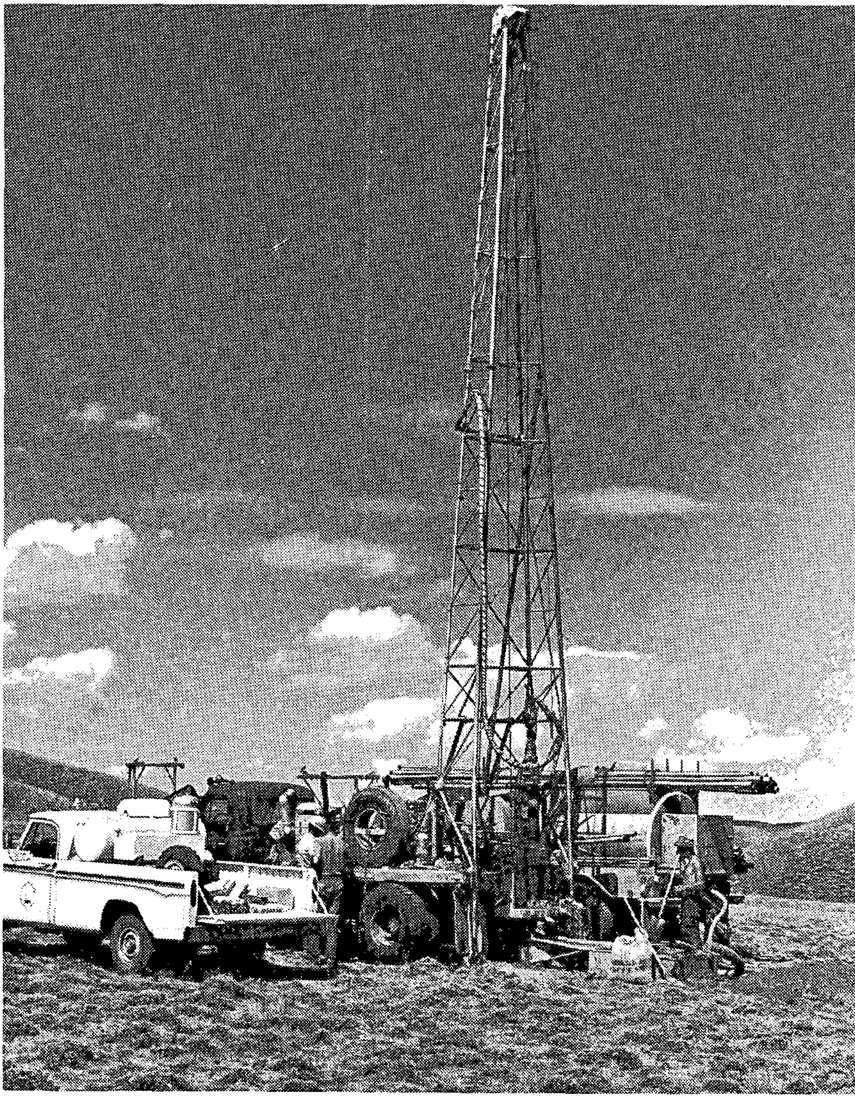

FIG. 4. Portable drilling rig in the Powder River Basin, Wyoming.

Auxiliary equipment usually includes a pick-up truck for crew and fuel transportation and equipment maintenance, a water truck capable of hauling 3000 (1000 gal) to 10 000 liters (3000 gal), and a portable steel mud pit. A major portion of the drill pipe is carried on the water truck. Normally both an air compressor and a mud pump are included as an integral part of the drill rig.

Supplies include several drag (or finger) bits and tri-cone type rock bits, the variety and number dependent on the conditions. Fluid conditioners

necessary are: drilling mud (usually bentonite in 23-kg bags), lost circulation material, and special additives to combat bad ground conditions. Developments in this field have greatly assisted in overcoming many difficult drilling problems. A visit from a drilling mud engineer is usually requisite in unknown areas. Modern drill rigs are powered by diesel engines which provide the necessary power for faster and deeper drilling and larger air compressors.

Operation of the drill is handled by an experienced driller assisted by one or two helpers. If several rigs are operated in one area, a "pusher" or foreman is often employed to coordinate and oversee the operation of all drilling personnel and equipment. Difficult and varied drilling conditions, complex equipment, a multitude of techniques, a knowledge of emergency procedures, etc. all require that drillers be the product of a two- or three-year training program as a driller's helper. A good driller is also a prerequisite for good samples and a properly conditioned hole, both of which are important for the collection of geological data.

Drilling rates vary from 30 m per shift in hard rock or other difficult conditions to more than 600 m per shift (in the case of some of the Tertiary formations of Texas and Wyoming). Cost is primarily dependent on the ability of the driller, rock hardness (speed and bit wear), hole depth and spacing, and previous knowledge of the area or rock type. In the USA, better equipment, improved techniques and experience have resulted in decreasing unit costs over the past decade. Contracts may be by the meters drilled, or by the hour. Direct costs in the USA range from slightly less than $1/m for the softer Tertiary sands and silts to over $13/m in hard conglomerates or very deep holes (500 m). Hourly rates range from $27/h to $45/h plus down-hole expendible supplies.

New techniques are constantly being developed to decrease costs or to permit drilling in previously impossible situations. The down-hole hammer drill, for instance, has been used successfully to drill granitic rocks at a cost of less than $6/m. Under proper conditions, reverse circulation drilling provides uncontaminated samples. The use of chemicals and stiff foam with air as a medium is improving penetration through certain types of unconsolidated rocks [2].

The operation of modern drilling equipment is a complicated science, achieving a high degree of efficiency and versatility owing to the experience of millions of feet of drilling in the last ten years. Anyone planning to use drilling in their exploration program should take full advantage of this expertise by starting with good equipment and experienced crews.

5.2. Geophysical logging

The gamma-resistivity logging unit is an essential tool for collecting data from drill holes.

In addition to detecting and accurately measuring uranium mineralization, the radiometric log can provide alteration data through analysis of certain gamma anomalies together with the lithologic and resistivity logs. Sensitive gamma detection equipment can also be used to assist in stratigraphic correlation.

The resistivity log is highly reliable for determining lithologic contacts and correlating rock units. Formational changes sometimes not apparent

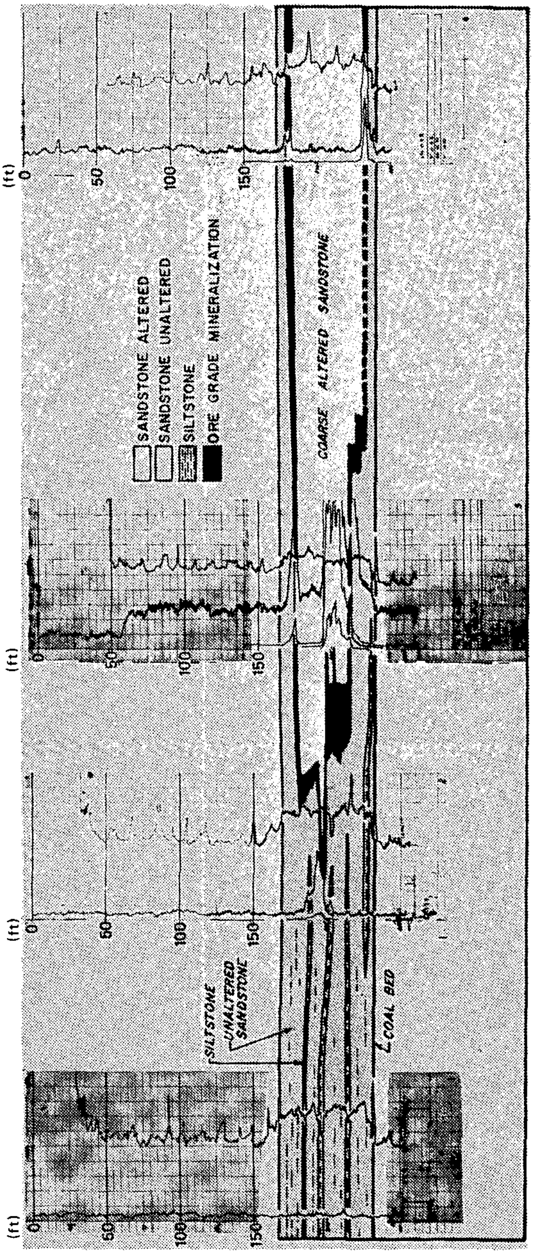

FIG. 5. Correlation of mineralization, stratigraphy and alteration using "mini-logs". On the upper logs, the left- and right-hand traces are the gamma and resistivity traces, respectively.

in the samples usually present themselves as a changing signature in the resistivity log.

Although usually at an original scale of 1:120 the logs can be photographically reduced to 1:600, which, when posted with pertinent sample data, allow rapid comparison and correlation with other logs. These "mini-logs" tend to smooth over the small details and accentuate the more important gross features of stratigraphy (Fig. 5).

The gamma logging units now in use provide an extremely accurate means of measuring the grade of uranium in the hole. The count within a 2-3-ft sphere is averaged, consequently offering a far better statistical look than a core hole. One disadvantage of the present gamma probes is that they do not determine uranium disequilibrium. In unoxidized deposits, where degree of disequilibrium is often relative to position with the ore body, a few strategically placed core holes will assist in making statistical adjustments. Oxidized or weathered deposits, on the other hand, are much more erratic and the gamma results should not be relied upon for reserve calculations. In this case air samples, if possible, are much cheaper than core samples.

Up-to-date equipment being used for ore measurements usually includes a digital printer which records the gamma count rate and depth. Analysis of the data is considerably easier with the digital record, since it is in a form to be punched for immediate computer input [3].

Although most uranium exploration has relied primarily on the gamma and resistivity logs, with some lesser use of the S. P. measurement, other techniques have potential value and continuing experimentation will undoubtedly lead to their increasing use to determine additional factors such as permeability, sulphide content and carbon content. Some of the methods are I. P., neutron-neutron, density, temperature, "long" and "short" normal resistivity and caliper logging. In deep holes or difficult drilling conditions, drift surveys are made to determine the direction and amount of hole deflection.

Modern logging equipment is much more reliable and accurate than most units in use ten years ago. Costs may vary from \$0.15/m to \$0.75/m, depending on quantity and type of service. Experienced contractors and operators are essential.

6. CONCLUSION

This paper has pointed out the many types of geological and geophysical evidence available only through the use of modern drilling and sampling techniques. This unique data, when coupled with seasoned interpretation, allows rapid determination of uranium resources in large geographic areas.

Drill hole information provides definitive, three-dimensional evaluation at a relatively low cost for reserves established.

ACKNOWLEDGEMENTS

Numerous government and industry geologists throughout the world have contributed to the knowledge of sedimentary uranium deposits. I am especially indebted to the uranium exploration staff of the Union Pacific

Mining Corporation and Mr. S. S. Merwin who helped make this presentation possible.

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DISCUSSION

J. A. FERNANDEZ POLO: When prospecting is carried out using drilling in regions such as those found in the sandstone areas of the United States of America, there is a first step which could be called initial prospecting on the basis of rather wide-spaced grids. It is thus possible to discover certain anomalies and to go to a more detailed stage of work. If nothing is found, of course the program is concluded. But when you get spurious anomalies within a limit of 5 to 10 times background, perhaps even greater values, what philosophy determines terminating a program? Could you perhaps explain this a bit further? What body of data obtained in such activities is

significant to justify proceeding to a more detailed study, or cutting it off at that point, both from the standpoint of economic data as well as of scientific data, radiometry, geology, geochemistry, etc. Is there anything published on this, for instance?

J. F. DAVIS: There are quite a number of publications, many more than I have listed in my paper. In answer to your first question, as I mentioned, the most difficult part of exploration is knowing when to stop and not proceed with an unnecessary waste of money, and I am certain that this can never be a finite definite point. However, I think that seasoned understanding of the geological and geometrical parameters which normally lead to the economic-sized ore bodies would be an important point. For instance, if you get an anomalous increase in radioactivity in a one-metre-thick sand, unless it were extremely high-grade, it would not be of importance other than to indicate the presence of uranium in the area. At this point one might then look for a thicker unit.

J. A. FERNANDEZ POLO: I have seen an interpretation of an already determined prospection program and it was shown how, given a certain drill hole grid, very few holes had been put down but the mineralized bodies found were significant. It is for this reason that I feel that with few data, but with very informative data determined from drilling, you should, in fact, be encouraged to continue the exploratory work.

J. F. DAVIS: Yes, I agree that it is important not to quit too early, particularly in the early stages, and these early stages should encourage a perhaps more subjective approach to the exploration. The conceptual idea is fine but exploration should contain a certain amount of subjective thinking as well. I have illustrated my case with known case histories because I feel this is perhaps the easiest way to proceed. Our company normally has approximately 12 to 20 projects at various stages of exploration and in a sedimentary situation this is normally the type of procedure we use. It is difficult to make any specific statement regarding the cut-off point on any one of the stages. Each one is decided on the basis of its own geological characteristics and, as Mr. Bowie pointed out, I definitely think the most important tool we have is the geological approach.

D. OSTLE: As a geologist, it is always satisfying for me to hear somebody virtually prove that it is better to abandon the purely statistical approach and rely on a geological skill, and to show that this is in fact good economics, because I think there is a tendency to believe that the same results can be achieved merely by putting down bore-holes on regular grids as can be obtained from the whole gamut of geological and geophysical investigations.

I have two questions, one an extension of that which Mr. Fernández Polo raised but relating to depth. Does the structure allow for the possibility of repetition of these rolls, down-dip in the sandstones, and what is the basis of the depth cut-off employed for exploration? Secondly, would Mr. Davis comment on the need for the apparent sophistication of determining disequilibrium. If these deposits are in overall equilibrium and if it is intended to mine the whole of the ore body, does it really matter whether the disequilibrium is known precisely at a particular point in it.

J. F. DAVIS: To answer your latter question first, in the case of an open pit mine, we had that experience in the early days in the Gas Hills, where I would say approximately double the overburden was removed that would have been necessary had we known the equilibrium. The so-called

limb or tail was enough out of equilibrium in favour of the radiometrics that we had interpreted it as ore when in fact it was not, so we could have made our pit much smaller in cross-section and our stripping ratio for the same amount of ore would have been approximately half of what it turned out to be — this is the important point.

As far as the progression down-dip of uranium-bearing solutions is concerned, it has occurred to us that perhaps all the uranium was not picked up at this one particular point. We have conducted exploration in these sand units beyond the roll fronts that we have discovered and apparently, if some uranium did leak through, it was not effectively precipitated at any successive point down-dip. Of course, the critical point here is to be able to identify the unit that you are in. As you know, in continental sediments this is somewhat difficult and one is never quite sure, until he gets down to the fairly detailed work, which vertical unit he is in.

H. H. ADLER: I think some of the developing countries may have to evaluate the economics closely. Perhaps $30 000 is not very much money, as you indicate, for drilling out the Gas Hills, but if you had 20 areas the size of the Gas Hills to choose from then, of course, you multiply $30 000 by 20 and you are getting up into significant figures. In your evaluation, considering the red altered sandstone which would possibly extend to the outcrop, can you determine by drilling basin-wards, presumably towards ore, whether indeed you are getting closer to ore from the characteristics, geochemical or otherwise, of that red sandstone?

J. F. DAVIS: We are in the process of doing some geochemical work. We have not been able to tell when we are getting close to ore other than by the change from hematite to the limonite type alteration in the case of the Powder River Basin. Many of these altered zones may terminate with no ore present or only very little mineralization. Very generally speaking, I think one can utilize the various aspects of the depositional characteristics of the fluvial deposits; for instance, areas that tend to have a greater amount of carbonaceous debris will more than likely have a better chance of ore accumulation; this might be an overbank situation or near the terminus of the coarse fraction of the sand.

J. CAMERON: Going back to the question of stopping exploration, this interests me very much and, as you very rightly replied to Mr. Fernández Polo, geological considerations enter into this. But probing deeper, do you ultimately have a real hard economic point at which you stop. For example, you are working on some area and you have proved X tons of mineral and it has a value but it is still not an ore body and your next hole is going to take your expenditure beyond Y% of your total content value. Is somebody going to say stop at that particular moment? Have you got a final economic criteria for stopping?

J. F. DAVIS: We have several projects that I think fit this category, and because we do have this present soft market situation, we attempt to get by with a minimum of maintenance cost or lease payment or what have you to hold the property and maybe perhaps do a very limited amount towards the valuation each year with the hope that eventually these reserves will pass, by reason of increased price or discovery of some higher grade ores, into a more positive category.

H. H. ADLER: I would like to raise one more question. This may be somewhat pertinent to Mr. Bowie's earlier paper concerning methods that can be used to identify favourable locations in the absence of radioactivity.

I presume that you were referring to hidden ore bodies showing no indication of radioactivity at the surface. Now this sandstone presumably outcrops and must have some manifestation of oxidation and is therefore probably a red or a limonitic sandstone at the surface. In the absence of radioactivity, have you any experience on evaluating the favourability of a red sandstone in a region where no uranium occurrences have been known to exist? How would one extrapolate your experience with sandstones in the western United States for example to Spain or to the eastern United States or to some other country where you have an abundance of fluvial sandstone but no indication of radioactivity, perhaps in a very wet climate? Is there some trace left within the overall red-altered zone that would reflect mineralization? And does this trace exist at the outcrop where it is easy to detect or observe?

J. F. DAVIS: Yes, as I mentioned earlier, I think the presence of a uranium province, or, generally speaking, of an area of uranium-rich rocks is important. Lacking knowledge of this, we are now exploring an area because it is known to be a low-temperature hydrothermal solutions area. There are a few scattered uranium occurrences, but not really enough to say it is a uranium province. But because it is in an area of low-temperature mineral or metal deposits of other types, we feel it is worthy of exploration and, specifically, I think a study of the geochemistry involved in the transport of uranium needs much more work.

H. H. ADLER: I think Mr. Davis has already given us a clue to a possible method, on which I can perhaps elaborate a little more in my paper, in regard to ascertaining the degree of abundance of ferromagnesian minerals in his altered sandstone as contrasted with the ferromagnesian mineral abundance in red beds that are developed under different circumstances.

ARTIFICIAL STANDARDS FOR CALIBRATION OF AIRBORNE, FIELD PORTABLE AND LOGGING GAMMA SPECTROMETERS

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Abstract

ARTIFICIAL STANDARDS FOR CALIBRATION OF AIRBORNE, FIELD PORTABLE AND LOGGING GAMMA SPECTROMETERS.

Gamma spectrometers used in prospecting for uranium ores are calibrated at calibration stations which may be located on natural geological structures, or constructed by artificial standards. Artificial standards should fulfil the physical and geometrical conditions of calibration of field gamma spectrometers. The shapes and dimensions of the standards for airborne, field portable and logging spectrometers are different. The shape of the gamma spectrum, the intensity of gamma radiation and the influence of the composition of the standard on the values measured in calibrating the apparatuses are discussed. The paper deals with problems concerning the standards containing loose material with a suitably chosen concentration of U, Th and K, which is enclosed in a firm envelope. The choice of material for manufacture of the standards, the radioactive equilibrium in the standards, the effect of the envelope of the standard and the dimensions and locations of the standards are treated separately. To enhance the accuracy of calibration, the radioactivity of the standards is chosen higher than that in rocks. The specified parameters of the standards for calibration of field gamma spectrometers can be applied in constructing a calibration base in an area where gamma-spectrometric measurements are to be carried out.

1. INTRODUCTION

Gamma spectrometric measurements introduced after 1960 into prospecting for radioactive raw materials [1-8] enable qualitative and quantitative determination of the individual radioactive elements in rocks. Gamma spectrometry is now used in airborne, ground and logging measurements with analogue or digital apparatuses [9, 10].

In gamma spectrometry using field apparatuses, the K, Ra and Th contents in rock are most often determined by detection of gamma radiation of ^{40}K (1.46 MeV), ^{214}Bi (1.76 MeV) and ^{208}Tl (2.62 MeV) [1, 4, 11, 12]. Under field conditions, direct determination of U using gamma spectrometry is very difficult [13]. Therefore, the determined content of Ra is used as an indicator of the presence of uranium in rocks. In general, the relation between the measured values $n_{1,2,3}$ in the selected gamma-energy intervals 1, 2, 3 and the concentrations Q_K, Q_{Ra}, Q_{Th} can be written in the form

$$n_i = a_i Q_K + b_i Q_{Ra} + c_i Q_{Th} \tag{1}$$

where i = 1, 2, 3 and a_i, b_i, c_i are the coefficients determined by calibration of the gamma spectrometer. If K, Ra and Th detection are chosen in the region of the peaks 1.46, 1.76 and 2.62 MeV and if a scintillation detector of sufficient resolution is available, then the values $a_2 = a_3 = b_3 = 0$, $n_1 = f(Q_K, Q_{Ra}, Q_{Th})$, $n_2 = f(Q_{Ra}, Q_{Th})$, $n_3 = f(Q_{Th})$ and the use of Eq. (1) leads

TABLE I. CONCENTRATION OF K, Ra and Th IN SELECTED GEOLOGICAL STRUCTURES IN BOHEMIA, CZECHOSLOVAKIA

Geological unit	Q_K (%K)	Q_{Ra} (ppm eU)	Q_{Th} (ppm Th)
Granulite massif of Prachatice	3.72	0.68	3.00
Granite massif of the Smrčiny Mts.	3.41	6.12	2.72
Granite massif of Kladruby	3.90	5.20	31.9

to the solution called the stripping method [4, 6]. Since n_i and a_i, b_i, c_i, are known, one obtains the values of Q_K, Q_{Ra} and Q_{Th} by solving Eq. (1).

The coefficients a_i, b_i, c_i are determined by calibration of a gamma spectrometer at the calibration base under the same physical and geometrical conditions as those of the field measurement.

2. CALIBRATION BASES FOR FIELD GAMMA SPECTROMETERS

Calibration of gamma spectrometers is carried out above natural geological bodies or above artificial radioactive bodies. The use of theoretical values or other methods to determine calibration coefficients leads to approximate calibration coefficient values [11, 14-16].

2.1. Calibration of field gamma spectrometers above natural bodies

For calibration, three geological structures are to be used, of which each has a typical higher concentration of one of the three radioactive elements. One should minimize the lateral variation of concentration of radioactive elements in rock and the vertical variation of the layer saturated with gamma radiation. The average values of the K, Ra and Th concentrations in selected geological structures in western and southern Bohemia [17] are shown as an example (Table I).

In calibrating gamma spectrometers above natural objects, the geometrical and physical conditions of calibration are fulfilled, and the determination of the effective values of the K, Ra and Th concentrations are the restricting factors in regard to estimating radioactivity variations in rocks.

By measurements above three geological structures, nine values n_i are obtained and, for the known concentrations Q_j, nine (or six) calibration coefficients a_i, b_i, c_i are determined. In practice, however, the constants of the explicit Eq. (5) corresponding to Eq. (1) are determined.

2.2. Calibration of field gamma spectrometers by artificial bodies

Artificial bodies which correspond to rock in their physical parameters are used in calibration. It is necessary to produce at least three standards, so that each of them contains higher concentration of one of the three investigated radioactive elements. It is difficult to prepare standards which would contain only one radioactive element (K, Ra, Th), and which would be advantageous for the determination of the calibration coefficients.

Calibration on artificial bodies is applicable to airborne, carborne, field portable and logging gamma spectrometers; for each type of equipment, standards of various shapes and sizes are used [14, 16, 18]. The advantage of the artificial standards is the relative homogeneity of radioactive elements in the standard and their suitable concentration; if the sizes of the standards are sufficient, they also fulfil the geometrical conditions of the measurements. Construction of large artificial standards is technically demanding.

The method of numerical determination of the calibration coefficients is the same as in the preceding case. The main problems of calibration on artificial bodies are discussed below.

3. STUDY OF THE GAMMA SPECTRUM OF LARGE BODIES

The gamma radiation spectrum of artificial standard bodies depends on the composition of the standard and on the radioactive element present.

3.1. The spectrum of gamma radiation of a point source and of large bodies

The relation between the shape of the spectrum of a point source and that of large bodies containing the same radiation source was studied by means of a Ra point source and a layer of a U ore (Fig. 1) [19]. Figure 1 shows that the characteristic peaks of 0.6, 1.12, 1.76 and 2.20 MeV appear in both sources, which are geometrically different. The differences in the relative intensity of the detected radiation in the $E < 0.4$ MeV region are due to the influence of the scattering properties of a material with $Z_{eff} = 14.5$, in which scattering of gamma rays of higher energies takes place.

Similar conclusions can be drawn from the results of the study of the gamma spectrum of the rocks, which was detected after penetration through air layers 1.8 -152 m thick [6]. This means that in measuring point sources as well as large bodies in the geometry $\omega = 2\pi$ or $\omega = 4\pi$ it is possible to identify the characteristic peaks and thus quantitatively determine the radioactive isotopes present.

3.2. Influence of the composition of the body

During passage of gamma rays of energy E_0 through a material, several interaction processes such as scattering, annihilation and production of

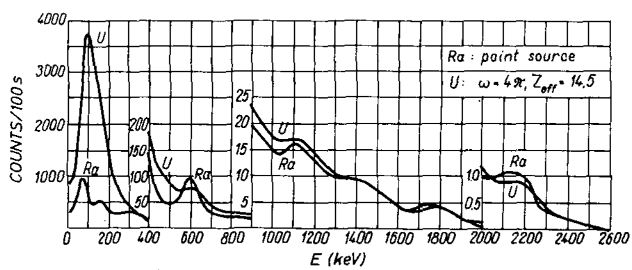

FIG. 1. Gamma spectra of a Ra point source and of an infinite layer of uranium ore (after Troitsky [19]).

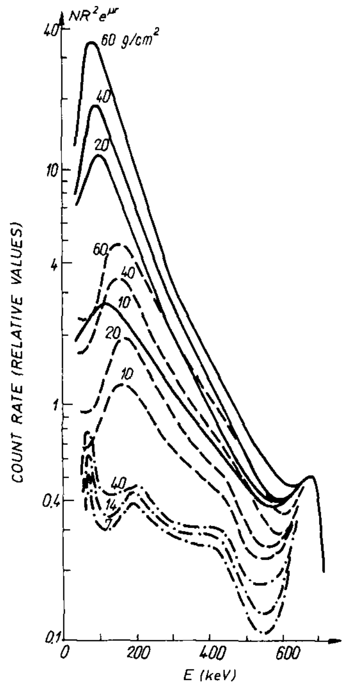

FIG. 2. Gamma spectra of ^{137}Cs after passage of gamma radiation through different materials, measured with a 2 mm Al filter. Sand: ——, Fe: ----, Pb: —·—. N: count rate, R: distance between source and detector, μ: linear attenuation coefficient, r: absorption layer thickness (after Artsybashev and Ivanyukovich [20]).

secondary gamma rays take place between the radiation and the atoms of the material. These processes result in gamma rays of energy $E < E_0$. The intensity of the detected gamma radiation and the shape of the gamma spectrum of the source (E_0) depend on the composition of the material and on its superficial density (Fig. 2) [20].

In interactions of gamma rays in the energy range E = 0.1 to 3 MeV with rocks, Compton scattering prevails and its cross-section is a function of the energy of the gamma rays

$$\sigma_C = f(E_0) \tag{2}$$

The macroscopic Compton scattering cross-section, ϵ_C, is expressed by the relation

$$\epsilon_C = n_e \sigma_C \tag{3}$$

where n_e is density of electrons. The difficult determination of n_e values for a medium containing several elements can be replaced by using values

TABLE II. AVERAGE VALUES OF DENSITY ρ, EFFECTIVE ATOMIC NUMBER Z_{eff} AND THE RATIO $2Z_{eff}/A_{eff}$ FOR FUNDAMENTAL ROCK GROUPS

Rocks	ρ (g/cm^3)	Z_{eff}	$2Z_{eff}/A_{eff}$
Light rocks	1.4	7	1.030
Medium-heavy rocks	1.6-3.2	7-16	1.0
Heavy rocks	4.0	20	0.970

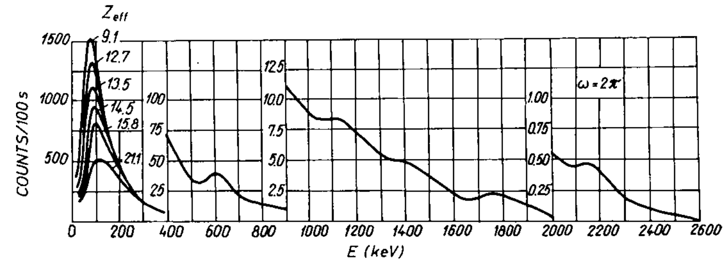

FIG. 3. Gamma spectra of uranium ores of different compositions (semi-infinite space) (after Troitsky [19]).

of the effective atomic number Z_{eff} and the effective mass number A_{eff} of the material. Equation (3) can be re-written as

$$\epsilon_C = \rho L \frac{Z_{eff}}{A_{eff}} \sigma_C \tag{4}$$

where ρ is the density (g/cm^3) of the material and L is Avogadro's number. Therefore the probability of Compton scattering is directly proportional to the values of ρ and Z_{eff}. The usual ratios between ρ, Z_{eff} and $2Z_{eff}/A_{eff}$ are shown in Table II.

In all mediums, the influence of the photoelectric effect increases with decreasing gamma-ray energy.

The dependence of the relative intensity of gamma radiation of various energies E from the source on the Z_{eff} of the source at a solid angle $\omega = 2\pi$ is evident within the energy interval 0-0.4 MeV (Fig. 3) [19]. Other authors [6, 7, 9] point out the broadening of the peaks in the apparatus spectrum of the scintillation radiometers in the energy region 0-1 MeV for $\omega = 2\pi$ and $\omega = 4\pi$.

To exclude the dependence of the measured values of the gamma radiation on the composition of rocks and on the induced characteristic radiation, as well as to eliminate low resolution of the spectrum, the field spectrometer measurements are carried out in the energy region E > 1 MeV. If these energy values are chosen, the effects of the differences in the composition of calibration standards and the rocks measured are minimized.

TABLE III. RELATIVE VALUES OF THE DECREASE OF GAMMA-RAY INTENSITY CAUSED BY DETECTOR SHIELDING

Filter	None	4 mm Fe	1.5 mm Sn + 0.5 mm Cu	4 mm Pb + 1.5 mm Sn + 0.5 mm Cu
Z_{eff} = 14.5	100	68	52	15
21.1	100	75	62	19

3.3. Shielding of detectors by absorption filters

The differences in the spectra of gamma radiation due to the different compositions of the measured rocks diminish if detectors are shielded by absorption filters. The differences in the gamma-ray intensity in the energy region E < 0.66 MeV for various Z_{eff} are substantially smaller than those if the detector is not shielded [19]. In using filters, the gamma-ray intensity progressively drops (Table III).

In measuring low values of the natural radioactivity of rocks, the measurement error would increase significantly if the detectors were shielded with filters. The latter can be used in logging measurements of the total gamma activity of uranium ore layers.

4. PHYSICAL PROPERTIES OF STANDARDS

From the results of Section 3 it follows that, for calibration of field gamma spectrometers, artificially produced bodies can be used as calibration standards. The standards can be constructed as rigid concrete thick plates [11, 17] or as a loose material enclosed in a firm envelope. Both kinds of standards have their advantages and disadvantages, among which are: the problems of technical construction, radioactive homogeneity, manner of sampling, influence of the envelope of the standard, conditions of the radioactive equilibrium and the emanation coefficient of the standard, influence of weather conditions on the standard, contamination of the standard, contamination of the environment by the standard, rigidity of the standard, size of the standard and possibility of its removal.

The choice of the way in which the standards are constructed also depends on the choice of radioactive elements concentration in the standards and the work safety at the calibration site. In Czechoslovakia, loose material enclosed in firm envelopes was chosen for constructing calibration standards. A minimum number of standards are considered.

4.1. Materials for production of standards

The standard is a mixture of the radioactive element and an inactive material. For the U-standard, a uranium ore which is in radioactive equilibrium can be used, and for the Th-standard, a thorium ore can be employed; for a K-standard, KCl is suitable. Quartz sand is a convenient medium which serves as an inactive material. Total gamma activity of such a sand, expressed in eU, should approach zero; the presence of Ra, Th and K should be determined.

TABLE IV. EMANATION COEFFICIENTS OF ROCKS (AFTER BARANOV [21])

Rock	Emanation coefficient (%)
Granite, granodiorite	17.0
Pegmatite	28.0
Quartz porphyry	4.5
Sandstone	10.7
Limestone	11.2
U-rich limonite	15.7

4.2. Radioactive equilibrium in standards

The state of radioactive equilibrium in the U-Ra and Th standards affect their gamma activity.

In U-standards, the U:Ra ratio should be $1:3.4 \times 10^{-7}$ or a value approaching this number. More than 95% of the gamma radiation of the ^{238}U disintegration series is emitted by the emanation disintegration products, including ^{214}Bi. It is therefore evident that the measured value in the ^{214}Bi window will depend on the emanation coefficient of the loose material of the standard. In a hermetically sealed standard, the emanation coefficient is zero. The disintegration products of ^{222}Rn, which have a short half-life (including ^{210}Pb), reach radioactive equilibrium after approximately 38 d. The gamma activity of the standard, measured in the energy regions of the gamma radiation of the ^{222}Rn disintegration products, will be higher compared with the rocks in which the emanation coefficient has non-negligible values (Table IV) [21].

In general it can be assumed that the gamma activity of a hermetized standard with $c_{em} = 0$ is 10-20% higher than that of the rocks with the same Ra concentration.

Thorium ores are usually in radioactive equilibrium. The ^{220}Rn disintegration products, including ^{208}Tl, attain radioactive equilibrium in a hermetized standard 106 h after sealing the standard. Gamma activity of the hermetized standard will again be higher than the gamma activity of the rocks with the same Th concentration.

4.3. Effect of the envelope of the standard

To judge the influence of the envelope of the standard (Al sheet 2-4 mm thick, superficial density of 4 mm Al is 1.08 g/cm^2) upon the gamma radiation of the source, the variations of shape of the gamma spectrum of a uranium ore and gamma absorption by the passage through Al filters 1, 2, 3 or 4 mm thick were examined under laboratory conditions.

The shape of the spectrum does not change after passage through an Al filter (Fig. 4). The characteristic peaks, 0.6, 1.12 and 1.76 MeV, can be used for quantitative determination of the radioactive isotopes of the source. The same conclusions can be drawn from the results of the study of the shape of the gamma spectrum of rocks after absorption by an air layer up to 195 m thick, using airborne gamma spectrometry [6, 10].

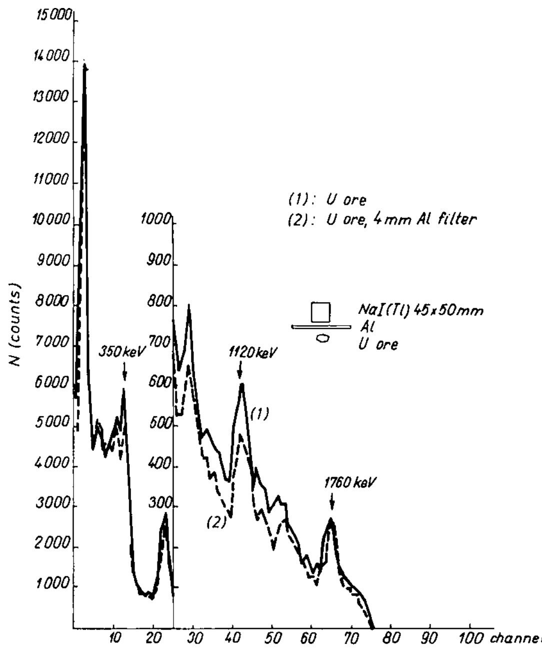

FIG. 4. Apparatus gamma spectra of uranium ore (1) without filter and (2) with 4 mm Al filter.

TABLE V. EXPERIMENTAL AND THEORETICAL VALUES OF GAMMA ABSORPTION BY Al FILTERS

	Total	1.46 MeV		1.76 MeV	
Filter	I_{exp} (%)	I_{exp} (%)	I_{th} (%)	I_{exp} (%)	I_{th} (%)
0 mm Al	100.00	100.00	100.00	100.00	100.00
1	95.85	92.22	93.70	90.95	94.00
2	94.24	87.49	89.10	91.85	89.80
3	94.08	86.68	85.30	90.25	86.30
4	93.97	83.59	82.00	84.,97	82.90

The absorption of gamma radiation by an Al filter was studied in measuring the total gamma activity (discrimination 50 keV) and in the windows set at the 1.46-and 1.76-MeV peaks. In Table V experimental values I_{exp} and theoretical values I_{th} calculated using the tabulated values of the linear attenuation coefficient $\mu(E)$ [22] are listed.

From the theoretical and experimental data it follows that the 2-4 mm Al filters lower the intensity I of the detected radiation in the windows of the 1.46-MeV and 1.76-MeV peaks by 10-18%, and the total gamma activity by 5-6%.

The total gamma-activity of hermetically sealed U and Th standards increases in relation to the rocks of equal properties by the value $c_{em}b$, where c_{em} is the emanation coefficient of rocks and b the proportion of the gamma radiation of the emanation disintegration products in the total gamma radiation intensity of the natural disintegration series. The usual values of these quantities are given in the literature [21]. The gamma activity for $E > 1.3$ MeV and in the windows 1.76 and 2.62 MeV increases in relation to the rocks of equal properties by the value c_{em}. According to Table IV [21] and the values in Table V, the activity increase in the hermetized standard (10-20%) is of the same magnitude as the decrease due to the absorption in the envelope (10-18%); both influences are therefore approximately compensated. For a K-standard which, owing to its humidity fluctuations, should also be sealed, the upper plate of the envelope should be chosen as thin as possible, or the real concentration of the standard, Q_K, should be corrected to the effective value($Q_K' < Q_K$) by an amount (expressed in per cent) corresponding to the absorption of gamma radiation in the standard's envelope, determined under the conditions identical to those used in measuring with a field gamma spectrometer.

4.4. Concentration of radioactive elements in standards

To maintain uniform conditions for measuring radioactivity of rocks and calibrating gamma spectrometers, the order of magnitude of the concentration of radioactive elements in the standards should agree with that of the same elements in rocks. Such a choice further depends on the use of large-size scintillation crystals of NaI(Tl), i.e. up to 48 000 cm^3 (3000 in^3) in volume, for high-sensitivity airborne spectrometry [11].

The usual airborne and carborne gamma spectrometry are carried out using smaller NaI(Tl) detectors, which still correspond to the requirements of the measurement accuracy. Typical volumes are 8200 cm^3 (500 in^3) for airborne gamma spectrometry and 330 cm^3 (75 × 75 mm) for field portable apparatuses. If low concentrations of radioactive elements in rocks are chosen, the relative measurement error in the count rate of the NaI(Tl) 75 × 75 mm detectors, for a measurement time of 5 min, have the values shown in Table VI. In using a field portable spectrometer with integration circuit (RC) the errors δn are substantially greater.

TABLE VI. RELATIVE MEASUREMENT ERROR OF THE COUNT RATE FOR A GIVEN CONCENTRATION OF K, Ra, Th IN ROCKS, NaI(Tl) 75 × 75 mm DETECTOR AND 5-min SAMPLING TIME

Window	K	Ra	Th
Concentration	3.3% K	3.5 ppm eU	15 ppm Th
Count rate (counts/min)	923	203	150
Relative error δn (%)	1.5	2.9	3.7

TABLE VII. Z_{eff} VALUES FOR VARIOUS U, Th AND K CONCENTRATIONS IN ROCKS

Standard	Q	Z_{eff}	Q	Z_{eff}	Q	Z_{eff}
U	3.5 ppm	10.80	35 ppm	10.80	500 ppm	10.83
Th	18 ppm	10.80	180 ppm	10.80	1500 ppm	10.89
K	3.34%	11.08	33.4%	15.34	52.44	18.05

The equation for the calculation of the concentration of radioactive elements has the form

$$Q_j = n_1 A_j + n_2 B_j + n_3 C_j \tag{5}$$

where j = K, Ra, Th.

From Eq. (5), one can obtain the following relation [23]

$$\delta Q_j \leqq \delta n_1 + \delta A_j + \delta n_2 + \delta B_j + \delta n_3 + \delta C_j \tag{6}$$

For $\delta Q_j \leqq 25\%$, corresponding to the normally admissible limits of error in the determination of Q, it follows that the constants A_j, B_j, C_j must be determined for the case given in Table VI with an average error of $\delta = 5.6\%$. Fulfilling the condition given by Eq. (6) is difficult because of the dependence of these coefficients on a_i, b_i, c_i. Diminution of errors in determining the constants A_j, B_j, C_j can be attained by increasing the concentration of radioactive elements in the standards, e.g. by about 5-10 times for field portable and airborne apparatuses and more for logging apparatuses with small-size scintillation crystals.

The variation of the gamma spectrum of a U-standard with increased concentration of the radioactive element is negligible up to a value of 0.1%U; in any case it appears only in the region of $E \leqq 0.3$ MeV [24].

In Table VII the values of Z_{eff} are given for various concentrations of radioactive elements in the standard with quartz sand. From the data it follows that the Z_{eff} variations are negligible in standards with U and Th, while in K standards the Z_{eff} values approach those of the medium-heavy rocks (Table II).

An increased concentration of radioactive elements in the standards is justifiable only in those cases where the detection error does not increase as a consequence of the dead time of the detector. The probability that all events will be registered can be expressed by the relation

$$p = e^{-n\tau} \tag{7}$$

where n is the count rate in counts/s and τ is the dead time of the detector of the order of 10^{-5} s. In order not to let the error of the dead time of the detector exceed 0.5% for an 8200-cm^3 NaI(Tl) detector, a K-standard with concentration $Q_K = 9.7\%$ K should be used. When this choice is made in a window of 1.36 to 1.56 MeV, a count rate of 500 counts/s can be expected and p = 0.9950; in the Ra and Th windows, count rates are less

TABLE VIII. VALUES OF RADII OF CYLINDRICAL STANDARDS FOR VARIOUS EFFECTIVE HEIGHTS OF THE DETECTOR; $\omega = 1.9\pi$, $x = 0.95$, $Q_{st} = Q_{rock}$

Gamma spectrometer	h (cm)	a (m)
Field portable	4	0.8
Field portable	5	1.0
Airborne	15	3.0
Airborne	100	30.0
Airborne	200	70.0

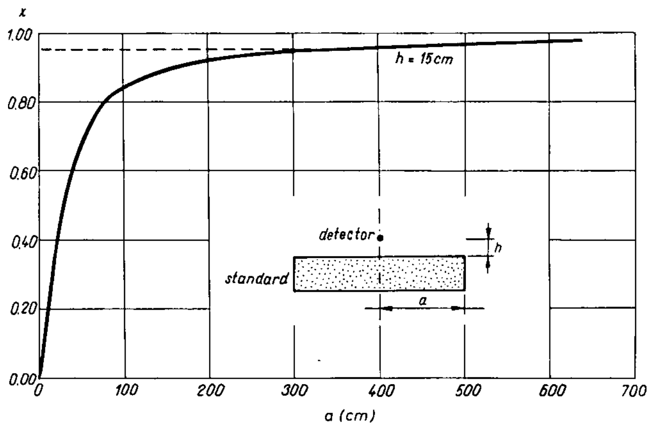

FIG. 5. Dependence of x ($x = I_h/I_0$) on radius a of the standard for h = 15 cm.

than this value. For the 330-cm^3 detector NaI(Tl) in the window 1.36 to 1.56 MeV at Q_K = 9.7% K, a count rate of 32 counts/s appears, p = 0.9997, and the count loss error is only 0.03%.

4.5. Dimensions of standards

The shapes and sizes of standards are determined by their intended use for various gamma spectrometers. For field portable and airborne spectrometers, cylindrical standards are convenient; in calibration, the detector is placed in the centre of the upper base of the cylinder. For logging gamma spectrometers, cylindrical standards are suitable which have a tube in the axis of the cylinder, where a probe of the logging device is placed.

The height of the cylinders of the standards intended for calibration of field portable and airborne gamma spectrometers should correspond to the layer saturated with gamma radiation (100 g/cm^2), i.e. for a

density of 1.6 g/cm^3 of a loose material of the standard, a height of 62 cm is necessary. Under these conditions, the gamma radiation, I_h, of the standard at the detection point at a height h above the centre of the upper circular surface S of the standard is obtained from the relation

$$I_h = I_0 \frac{h}{2\pi} \iint_S e^{-\mu r} r^{-3} dS \tag{8}$$

where I_0 is the intensity of gamma rays at a height 0, μ is the linear attenuation coefficient in the air, and r is the radius vector from the detection point to the points of the surface S. Equation (8) can be written as

$$\frac{I_h}{I_0} = f(a, h, \mu) \tag{9}$$

from which the radius a of a cylindrical standard can be calculated if h and μ are given and if a value of I_h/I_0 is chosen; $(I_h/I_0 = x)$. [16] For the location of detectors of field portable gamma spectrometers on the standard, a height of 5 cm can be used, while for airborne apparatuses the height is 15 cm. If the detector were left in the aeroplane, this would correspond to a height of 100 or 200 cm.

In calibrating gamma spectrometers it is necessary to detect the prevailing gamma radiation of the standard. The situation is satisfactory, when x = 0.95, that is, when the standard contributes 95% of the radiation detected, while only 5% of the detected radiation comes from the surrounding rocks.

In Table VIII, radii of cylindrical standards for various detectors are given for the condition x = 0.95, assuming that the concentration of radioactive elements of the standard equals that of the surrounding rocks. The values have been calculated on the basis of the Eq. (9). In Fig. 5, the radius a is shown as a function of x for h = 15 cm.

If the detectors are left in the vehicles, it follows from the values in Table VIII that the standards intended for calibration of airborne or carborne gamma spectrometers would be unsuitable and their technical manufacture very difficult. It is therefore necessary to place the detectors of these devices directly on the upper surface of the standard.

As has been shown in Section 4.4, it is advisable to enhance the concentration of radioactive elements in the standard in relation to that of the surrounding rocks, i.e. $Q_{st} > Q_{rock}$. Under these conditions the radii of the standards for x = 0.95 are substantially smaller (Table IX).

TABLE IX. VALUES OF RADII OF CYLINDRICAL STANDARDS FOR VARIOUS EFFECTIVE HEIGHTS OF THE DETECTOR; $x = 0.95, Q_{st}/Q_{rock} = 10$

h (cm)	a (m)	ω (π)
4	0.11	1.32
15	0.45	1.38
100	2.50	1.26
200	5.00	1.26

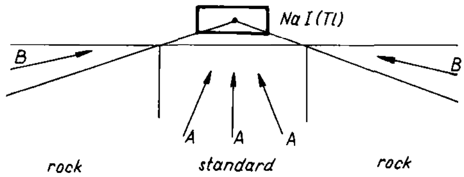

FIG. 6. Detection of gamma rays from different directions.

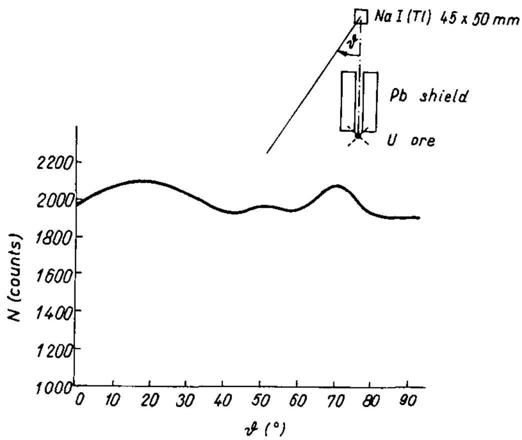

FIG. 7. Directional efficiency of the NaI(Tl) 45 × 50 mm detector.

In using the layers saturated with gamma radiation, the radius for h = 4 cm must be corrected to 0.62 m. The standard for the airborne apparatus with detectors 6 × 4 (150 × 100 mm) and h = 15 cm must have a radius at least of 0.80 m. The solid angles of detection, however, are substantially lower than $\omega = 1.9\pi$ for these values, and the gamma rays emitted by the standard in the direction A will have a different direction from that of the gamma rays detected in measuring the rocks (directions A and B, Fig. 6). Taking into account the directional anisotropy of non-isometric scintillation crystals NaI(Tl), which has been confirmed experimentally and theoretically [16,25,26]. (Fig. 7), appreciable errors in the measured values would be caused by the different conditions of the directional acceptance of gamma rays in calibrating on a small standard ($\omega = 1.5\pi$) and in field measurements ($\omega = 2\pi$).

From the directional efficiency of the NaI(Tl) crystals, it can be concluded that in calibrating field portable and airborne spectrometers it is not suitable to use standards for which the solid angle of the detection is lower than 1.9π, even if $Q_{st} > Q_{rock}$.

TABLE X. SIZES OF CALIBRATION STANDARDS AND CONCENTRATION OF RADIOACTIVE ELEMENTS IN THE CALIBRATION STANDARDS FOR FIELD PORTABLE, AIRBORNE AND LOGGING GAMMA SPECTROMETERS

	Standard		Concentration of radioactive elements			ω	x
Gamma spectrometer	a (m)	h (cm)	(% K)	(ppm U)	(ppm Th)	(π)	(%)
Field portable	1.0	0.62	9.7	30	80	1.9	
Airborne	3.0	0.62	9.7	30	80	1.9	99.5
Logging	0.7	1.20	52.44	500	1500	4	100

The sizes of cylindrical calibration standards for logging gamma spectrometers must fulfil the condition of detection in the geometry $\omega \to 4\pi$. The thickness of the layer of the active material surrounding the detector should correspond to the layer saturated with gamma radiation.

In Table X suitable sizes of standards and radioactive element concentration in the standards for field portable, airborne and logging gamma spectrometers are shown. It is clear that the calibration standards for airborne spectrometers correspond fully to calibration geometrical requirements for field portable equipment.

For logging apparatuses it is convenient to construct a fourth standard containing inactive sand for the determination of the natural background.

The artificial bodies of the standards for calibration of field gamma spectrometers can conveniently be placed in a region of the rocks showing a very low and slightly variable radioactivity. The bodies for field portable and airborne gamma spectrometers are sunk into the ground, their upper surface remaining at the level of the ground. The distance of the centres of the individual standards, positioned in the sequence K, Ra, Th, is 15 m (field portable) or 20 m (airborne). The standards for logging gamma spectrometers are 0.5 m under the surface of the ground, the vertical axes of the bodies being 5 m apart.

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FUTURE DEVELOPMENT IN THE USE OF GAMMA-RAY SPECTROMETRY FOR URANIUM PROSPECTING ON THE GROUND

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Abstract

FUTURE DEVELOPMENT IN THE USE OF GAMMA-RAY SPECTROMETRY FOR URANIUM PROSPECTING ON THE GROUND.

The significance of a uranium anomaly can often be most readily estimated from γ-spectrometric measurements of the ratio between the concentration levels of uranium, thorium, and potassium. This technique lends itself to remote sensing from aircraft, surveying by car or on foot, and examination of collected material. Today, a large selection of γ-spectrometers especially designed to meet the uranium prospector's requirements are commercially available, and even more compact, high-performance instruments can be expected on the market in the future. However, statistically meaningful radioelement determinations can only be made if sufficiently large scintillation crystals are used, so there is a lower limit to the size and weight of any usable γ-spectrometer. Successful use of portable γ-spectrometers depends on the future availability of suitable calibration standards at strategic places in or near the world's major uranium districts. Future possibilities for fast interpretation of uranium anomalies are largely dependent on the efficiency in the use of digital computers for the processing of γ-spectrometric data.

1. INTRODUCTORY REMARKS

The starting point for the discussion presented here is the growing recognition of the fact that true uranium anomalies manifest themselves most distinctively, as far as their γ-ray emission is concerned, by a relative enrichment in uranium with respect to thorium and/or potassium. This phenomenon implies that the ratio U:Th:K, as determined by γ-spectrometric techniques, is a most useful object of investigation in the prospecting for uranium resources.

The above statement is especially relevant in connection with aeroradiometric surveying, among other things because the experimental errors arising from minor lateral displacements between ^{214}Bi and parent ^{238}U are negligible in remote sensing by γ-spectrometry. Most convincing evidence of the significance of the ratio between the radioelements in aeroradiometric surveying has recently been given by Darnley [1]. Though direct γ-spectrometric assaying of terrestrial material is a less powerful technique than airborne γ-spectrometry, it seems reasonable to assume that γ-spectrometers could be used with advantage for ground prospecting purposes.

It should be kept in mind that much primary uranium prospecting will continue to be made on the ground, especially where aeroradiometric surveying is impracticable for financial or other reasons. As an increasing percentage of the world's uranium resources must be sought in areas with sparsely developed road systems, most ground surveying will have to take place on foot, with or without transportation support from helicopters.

Consequently the light-weight portable γ-spectrometers which are commercially available to-day are very suitable.

The applicability of portable γ-spectrometers for in situ analysis of the radioelements has already been demonstrated fairly well [2, 3, 4]. As the exploration geologists learn to appreciate the performance of the modern, portable γ-spectrometers, these will probably become common equipment on ordinary field traverses so that radioactive anomalies caused by thorium and potassium can be discarded on the spot. It is important that a portable γ-spectrometer can also be used for integral γ-ray counting, whose importance as a general guide to radioactive occurrences is unquestionable.

In addition to the expected future role of portable γ-spectrometers, the possibility of using stationary or transportable γ-spectrometers in field camps also deserves attention. Much time could be saved if collected rock specimens were analysed for radioelements close to the exploration area rather than being dispatched to a distant analytical laboratory.

Below, an attempt is made to highlight some important factors which must be considered when a purchase or a design of γ-spectrometric instrumentation for use on the ground is made. This discussion, which is based on the fact that a precise determination of radioelement contents presupposes excellent instrumental stability and good counting statistics, is followed by a consideration of the calibration problem in the use of portable γ-spectrometers. Finally, ideas are presented on the future development of γ-spectrometric instrumentation and techniques for uranium prospecting.

2. THE PRECISION OF γ-SPECTROMETRY

The preferred γ-spectrometric method of assaying Th, U, and K consists in simultaneous γ-ray counting in three energy intervals, or "windows", each about 250 to 300 keV wide and centred at 2.62, 1.76, and 1.46 MeV respectively. Neglecting the small contribution from uranium 2.2- and 2.4-MeV γ-rays to the count rate in the 2.62-MeV window, the radioelement contents can be determined from the equations

$$
\begin{aligned}
\mathrm{Th} &= C_T n_T, & n_T &= n_{2.62} - b_{2.62} \\
\mathrm{U} &= C_U n_U, & n_U &= n_{1.76} - b_{1.76} - \alpha n_T \\
\mathrm{K} &= C_K n_K, & n_K &= n_{1.46} - b_{1.46} - \beta n_T - \gamma n_U
\end{aligned}
\qquad (1)
$$

In these equations, the letters n and b stand for total count rate and background count rate respectively, while α, β, and γ denote the all-important "stripping" ratios which compensate for the influence of thorium in the 1.76-MeV window and the influence of both thorium and uranium in the 1.46-MeV window. C_T, C_U, and C_K are calibration constants used for conversion of the corrected count rates to ppm Th, ppm equivalent U, and % K. Table I shows measured calibration constants and stripping ratios applying to in situ analysis by 2 × 2" and 3 × 3" detector crystals and laboratory analysis of 230-g samples by a 5 × 5" detector crystal.[1]

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[1] The symbol " denotes inches and cpm denotes counts/min throughout this paper.

TABLE I. CALIBRATION CONSTANTS AND STRIPPING RATIOS OF THREE DIFFERENT γ-SPECTROMETRIC MEASUREMENT SYSTEMS

NaI(Tl) crystal	C_T (ppm/(counts/min))	C_U (ppm/(counts/min))	C_K (%/(counts/min))	α	β	γ
2 x 2 in.[a]	0.63	0.16	0.019	1.7	2.3	1.5
3 x 3 in.[a]	0.14	0.036	0.0048	1.2	1.6	1.3
5 x 5 in.[b]	1.43	0.36	0.039	0.51	0.81	1.03

[a] In situ analysis of outcrops.
[b] Laboratory analysis of 230 g material.

There are three important factors which govern the precision in the determination of the corrected count rates n_T, n_U, and n_K. These factors are: The strength and the variability of the γ-ray background; the stability of the counting windows with respect to the γ-ray energy; and the number of counts accumulated in the three windows during the time of measurement.

2.1. Considerations Regarding the γ-Ray Background

The natural γ-radiation environment at ground level has its origin mainly in the contents of U, Th, and K in the uppermost part of the earth's crust. Cosmic radiation and airborne or precipitated radon daughters are normally less prominent contributors to the natural γ-ray flux. In situ analysis for U, Th, and K by γ-spectrometry therefore has a favourable signal-to-noise ratio. On the other hand, when γ-spectrometry is used for analysis of collected sample material, the natural γ-ray flux represents in its entirety a background source whose influence must be suppressed by careful shielding of the γ-ray detector. The shielding thickness required typically amounts to 15 cm of iron, but even a well-designed stationary or transportable laboratory γ-spectrometer still shows a 1.76-MeV background which is equivalent to a sample content of between 1 and 10 ppm U. The fact that the corresponding figure in the case of in situ analysis is about an order of magnitude lower is one of the reasons why field assaying is preferable to laboratory assaying.

The variability of the γ-ray background, if any, is generally caused by a high and variable radon content in the atmosphere. This phenomenon, which may occur even at considerable distances from uraniferous formations, may prevent high-sensitivity, γ-spectrometric field assaying. Planning of surveys with portable γ-spectrometers therefore requires some knowledge of the atmospheric radon levels in the area to be explored.

2.2. The Necessity for High Instrumental Stability

The calibration constants and the stripping ratios in equations (1) are quite strongly dependent on the energy limits which define the counting windows. Uncontrolled variations in the electronic gain of the γ-spectrometer therefore give rise to measurement errors. With the use of a portable γ-spectrometer equipped with a 3 × 3" scintillation crystal the author has

observed that errors of 1% and 6% on the measured contents of Th and U, respectively, result from a gain shift of 1%. Whereas pulse amplifiers and discriminators designed on the basis of contemporary circuit technology are little influenced by temperature and supply-voltage variations, even modern photomultiplier tubes are basically unstable devices whose necessity in high-efficiency γ-ray detection is most unfortunate. Thus, in the design of γ-spectrometers for field use one must count on the fact that the gain of a photomultiplier often shows a (negative) temperature coefficient of 0.5%/°C.

It is essential that the continuous monitoring and adjustment of the spectrometer gain which is required in the changing temperature environment presented by nature can be carried out automatically, as the prospector should not be encumbered with technical operations apart from recording of counts. At the present time, automatic gain-stabilization systems which are based on the use of low-energy γ-ray reference sources seem to be the most feasible ones for incorporation in both ground and airborne γ-spectrometers. A portable γ-spectrometer developed by AERE, Harwell, is stabilized by the 60-keV γ-rays from a 0.1-μCi ^{241}Am source attached to the inside of a cup-shaped crystal cover which forms a graded filter for the low-energy part of the external γ-radiation. The system, which has eliminated the need for a high-voltage control knob, is capable of reducing the photomultiplier gain-drift by a factor of ten [5].

2.3. Counting Statistics Considerations

The precision of any γ-spectrometric assaying is ultimately governed by the number of counts accumulated in the counting windows, and hence by the volume of the detector crystal when the counting time is given. It is probably correct to say that surveying by portable γ-spectrometers is only of practical interest if the particularly important U:Th ratio can be determined with a precision of about ± 15% in a few minutes. At least, γ-spectrometers should not be much slower to use than ordinary scintillation counters.

Assuming that the background count rates are constant and precisely known, it follows from equations (1) that the relative standard deviation of the measured U:Th ratio is given by

$$\sigma_{U:Th} = \frac{n_{1.76} - b_{1.76}}{n_{1.76} - b_{1.76} - a(n_{2.62} - b_{2.62})} \times$$

$$\sqrt{\frac{1}{\tau}\left[\frac{n_{1.76}}{(n_{1.76} - b_{1.76})^2} + \frac{n_{2.62}}{(n_{2.62} - b_{2.62})^2}\right]} \times 100\% \quad (2)$$

where τ is the counting time. With a U:Th ratio of 0.3, Fig. 1 shows the counting time resulting in $\sigma_{U:Th}$ = 15% as a function of the uranium content. The three curves in the figure were calculated on the basis of equation (2) and with the U and Th calibration data given in Table I. The values of the background count rates $b_{1.76}$ and $b_{2.62}$ were assumed to be 6 and 2 cpm for the 2 × 2" field spectrometer, 15 and 5 cpm for the 3 × 3" field spectrometer, and 24 and 11 cpm for the 5 × 5" laboratory spectrometer.

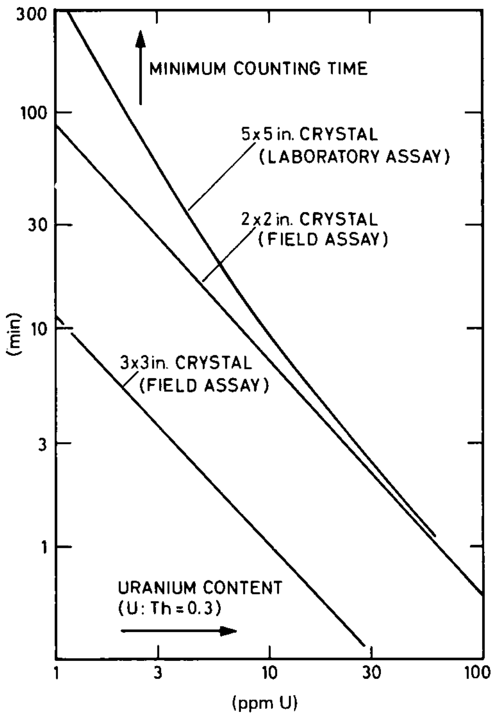

FIG. 1. Counting times required to obtain a relative standard deviation of 15% on a measured U : Th ratio of 0.3.

The most important conclusion which can be drawn from Fig. 1 is that γ-spectrometric surveying with a 3 × 3" crystal can be done 7 times as quickly as with a 2 × 2" crystal. The improved performance of the 3 × 3" system over the 2 × 2" system is mostly due to the 4.5 times greater window count rates produced by the former, but the smaller value of the stripping ratio α (Table 1) also makes the 3 × 3" system more efficient. It is noteworthy that a 3 × 3" crystal permits reasonably precise assessments of the U:Th ratio to be made in less than 10 min in virtually all geologic environments that encourage uranium prospecting. In granitic areas (U ≈ 3 ppm) a counting time of about 3 min will generally be sufficient. A 2 × 2" crystal, on the other hand, must generally be considered inadequate for use in field γ-spectrometers, as pointed out by Darnley at an earlier occasion [6]. It is therefore regrettable that the standard detectors delivered by the manufacturers of portable γ-spectrometers are normally equipped with 2 × 2" or even smaller crystals.

Fig. 1 also provides a strong argument in favour of field assaying versus laboratory assaying. The counting time required for γ-spectrometric analysis of a few hundred grams of material with U ≈ 3 ppm and Th ≈ 10 ppm amounts to about one hour. Furthermore, the initial cost of a carefully shielded, high-performance laboratory γ-spectrometer is 3 to 4 times that of a field γ-spectrometer. It is indeed "more efficient to take the instrument to the sample than taking the sample to the instrument" (slightly paraphrased quotation from ref. [2]).

3. CALIBRATION OF FIELD γ-SPECTROMETERS

The stripping ratio α in equations (1) results from Compton scattering of 2.62-MeV thorium γ-rays into the 1.76-MeV counting window, and the stripping ratios β and γ similarly reflect the fact that γ-rays from both thorium and uranium are Compton scattered into the 1.46-MeV counting window. The scattering events take place both in the sample material and in the detector crystal, so the values of the stripping ratios are generally smaller, the smaller the volume of the sample and the greater the volume of the crystal (cf. Table 1). In field assaying, the sample is very large, which implies that the stripping ratios as well as the calibration constants C_T, C_U, and C_K must be determined from calibration measurements of "infinite" γ-ray sources.

3.1. Concrete Calibration Standards

The most attractive kind of γ-spectrometer calibration source is an artificial one whose radioelement contents and homogeneity can be properly controlled by a suitably chosen manufacturing method, and which can be set up at any desired location. Concrete with an admixture of natural radioelements is undoubtedly the cheapest source material whose composition most closely fits the composition of ordinary crystalline rocks. Large-area (58 m^2) concrete calibration standards permitting calibration of both ground and airborne γ-spectrometers have been constructed in Canada [7]. Smaller standards exclusively designed for the calibration of portable γ-spectrometers were recently constructed in Denmark at the Research Establishment Risø. Though the performance characteristics of the Risø standards are not known in full detail yet, the following information will indicate that the construction of such standards is in no way very expensive nor does it present any insurmountable difficulties.

The Risø calibration standards comprise four concrete slabs, 3 m in diameter and 0.5 m thick, which form a line of working platforms level with the terrain. The three standards contain about 200 ppm U, 150 ppm Th, and 7% K respectively, while the fourth contains less than 1 ppm U, 3 ppm Th, and 1% K. The latter standard serves as a zero-reference which eliminates the need for any separate background determination. High-grade, finely ground uranium ore and monazite sand were used as radioactive admixture for the uranium and thorium standard respectively. About 50 portions of 370 g radioactive material, 110 kg sand, and 42 kg cement were mixed for 5 min each in a 150-l rotating mixer; then water was added, and the concrete was poured into a form. The potassium standard was prepared similarly, using potassium feldspar, separated by flotation, with 10% K instead of sand. No radioactive material was added in the construction of the zero-reference standard.

The manufacturing process described above appears to be quite efficient. The raw materials used are easy to procure, and three men can easily make a standard in one day. The Risø standards, which were used for the measurement of the field γ-spectrometer calibration data given in Table I, seem to be very homogeneous, and no significant radon escape from the uranium standard has been detected so far. A more widespread use of portable γ-spectrometers can only be expected if similar or improved calibration standards become available at strategic places in the world's present and future uranium exploration areas.

4. THE FUTURE DEVELOPMENT OF γ-SPECTROMETRIC TECHNIQUES

The following discussion is an attempt to establish recommendations for the future use of portable γ-spectrometers in primary uranium prospecting. The essence of the ideas presented is the desirable future availability of a novel, high-performance field γ-spectrometer which in fact could be designed today already on the basis of the existing electronic technology.

4.1. Optimum Ground Surveying by γ-Spectrometry

Fig. 2 will serve to visualize the author's suggestion of an expedient γ-spectrometric technique for use in field traverses on foot. The hypothetical, backpack-mounted γ-spectrometer shown weighs less than 10 kg, 2 kg of which is contributed by the 3 × 3" crystal-photomultiplier assembly. The unit contains, in addition to the γ-ray detector, all γ-spectrometer electronics, a simple digital computer, a dry-cell battery pack, and, possibly, a compact, cassette-type digital tape recorder. The operation and the reading of the instrument are carried out by means of a small control unit fastened to the geologist's belt. A front-panel meter is used for continuous monitoring of the integral γ-ray count rate, while the γ-spectrometric results are presented on a multi-decade, numerical display at the end of a counting interval.

The reason why the γ-ray detector should be worn on the back is that, besides the desirability of having the hands free, it is advantageous to raise the detector as much as possible above the terrain surface. Thus,

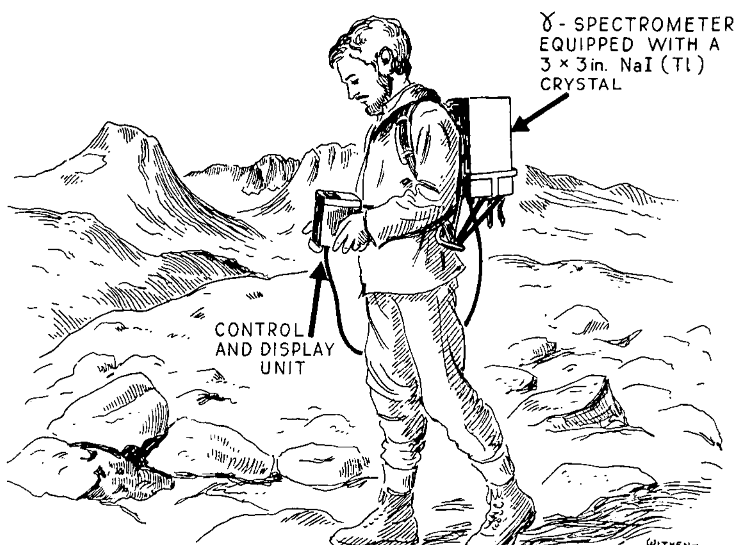

FIG. 2. An artist's rendering of the author's suggestion of future ground surveying by γ-spectrometry.

the greater the detector elevation, the greater the area covered by the γ-spectrometer in a single measurement. Good ground coverage is generally desirable, among other things in order to ensure that the assay values may be considered representative of the field localities. With a distance of about 1.5 m between the detector crystal and the ground, the effective viewing area of the γ-spectrometer is of the order of ten metres in diameter. A further improvement in ground coverage can be obtained if the geologist keeps on walking while counts are being accumulated, as indicated in Fig. 2. Whether a steady forward movement or a movement in a zigzag pattern should be preferred is a matter of prospecting philosophy, whose basis is the requirement of a minimum counting time of about 3 min in most geologic environments.

It is noteworthy that while deviations from the 2π detector-to-source geometry aimed at in field γ-spectrometric assaying will affect the accuracy of the measured radioelement contents, such deviations have virtually no effect on the accuracy of the assayed radioelement ratios. The information provided by the latter is therefore the most trustworthy in exploration by γ-spectrometry of very rough terrains.

The incorporation of a digital computer in a portable instrument may seem very advanced and highly extravagant. However, as the net 1.76-and 1.46-MeV window count rates are not proportional to the concentration levels of uranium and potassium at the field localities, it is most important that the stripping correction of these count rates can be made on the spot. Assuming that both the γ-spectrometer stripping ratios and calibration constants are known, an immediate conversion of all three window count rates into real radioelement concentration units should definitely be aimed at. The accomplishment of an automatic data reduction based on equations (1) would only require computer hardware of very small dimensions and low power consumption, cf. the fact that pocket-size electronic calculators are now on the market. Calibration and background data could conveniently be read in by means of a small keyboard on the side of the control unit, which furthermore should permit a choice between a display of the window count rates, the calculated contents of U, Th, and K, and the ratios U:Th, U:K and Th:K.

4.2. Processing of γ-Spectrometric Data

In spite of the fact that the major advantage of field γ-spectrometric surveying lies in the immediate guidance obtained on the nature of radioactive anomalies, the investment in equipment and manpower required for this kind of work can only be justified if all assay values can be permanently saved. As the field activities in a certain area normally stretch over several years, the γ-spectrometric information on the potential uranium resources of the area is picked up gradually. The results of both ground and airborne surveys by γ-spectrometry should in general go on a permanent file, which is kept up-to-date, and from which a picture can at any time be obtained showing the status of the field assaying, e.g. in the form of a plot of all assay values on a geologic map.

The maintenance and the handling of data files with many records is most conveniently carried out at a well-equipped computer centre. In the use of the computer facilities, an automatic registration of assays obtained in ground surveying with portable γ-spectrometers would be of great value. As suggested in subsection 4.1, one possibility is to have a simple, digital tape recorder installed in the γ-spectrometer. Improved means of ensuring efficient communication between the field camp and the computer

centre should also be developed. The use of two-way data transmission by radio is probably the only practical solution as far as uranium exploration in remote areas is concerned.

CONCLUSION

Although γ-spectrometric prospecting for uranium is most economically carried out from aircraft, ground surveying by γ-spectrometry must also be considered an expedient technique, especially where aeroradiometric surveying is impracticable. The future field γ-spectrometer is easily carried and capable of measuring radioelement concentration levels, expressed in ppm eU, ppm Th, and % K, in the course of a few minutes. An instrument like this could well be designed already today. The absolute calibration of field γ-spectrometers is most easily carried out with artificial calibration standards in the form of radioactive concrete slabs.

ACKNOWLEDGEMENTS

B. Leth Nielsen of the Geological Survey of Greenland offered valuable criticism of the manuscript. The uranium ore used in the construction of concrete calibration standards was kindly supplied by the Eldorado Nuclear Ltd., Saskatchewan, Canada. The calibration measurements used in the preparation of Fig. 1 were carried out by P. Sørensen and E. Johannsen. Fig. 2 was drawn by Ib Withen.

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DISCUSSION

A.G. DARNLEY: I am very interested in these approaches to the problem of calibration. I know Mr. Løvbord's approach has benefitted from our own experience in Ottawa on this particular problem. I am just wondering if he can tell us the composition of his raw concrete – what was its radioelement content?

L. LØVBORG: About 2 ppm thorium, 1 ppm uranium and 1% potassium.

A.G. DARNLEY: The biggest problem that we experienced was in ensuring consistency in the raw concrete itself, since the aggregate used in the concrete showed some variability and this is something which must be monitored and avoided. I think ideally one would like to specify an inert aggregate, either limestone or a clean quartz gravel, but it is not always very practical to do this.

L. LØVBORG: In our case it would been very expensive to order particular raw materials for the concrete. I might add that we weighed the cement very carefully and, as regards the sand, we used standup plastic 20-litre buckets so the sand was added on a volume basis.

H.H. ADLER: Not knowing very much about the operation of these hand-carried spectrometers but noting from the experience of one of my colleagues, there have been some real knotty problems in putting these instruments to practical use. We have no capability for maintaining these instruments and have been plagued by consistent failures involving battery recharging. Also, the battery recharge times are considerable. The instruments sound fine on paper but unless you are very well-versed in electronics and can troubleshoot them, which is impossible if you put an inexperienced man in the field with this piece of equipment, particularly in some remote country, you are going to have considerable expense for maintenance. I admit this is a rather pessimistic outlook and perhaps it stems from unfortunate experience with a particularly difficult instrument. Would you like to comment on the practical aspects of a geologist, with no electronics background, using such a sophisticated instrument in the field and the logistical support required for it?

L. LØVBORG: I admit that in the past it has been a big problem to use electronic instruments in the field, but I think that this will be no problem really in the future, because electronic circuitry is becoming more and more reliable. The designers of these instruments can learn a lot from the space project people who are able to use much more sophisticated instruments than these on the surface of the moon. It would be wrong to try to educate geologists to troubleshoot electronic instruments. Instead, the manufacturers must be forced to make the instruments more reliable and I think that they are willing to do so. Regarding the batteries, manufacturers today prefer to make use of dry cell batteries and mercury batteries, which are much more reliable than rechargeable batteries.

D. OSTLE: I think there is a need for a compromise to be reached between reliability and cost. As Mr. Løvborg well knows, the simple operation of hermetically sealing a piece of equipment can put the cost up enormously. To achieve this feat of reliability one must have hermetic sealing, and yet the instrument manufacturer, if he is to try to make some sort of profit out of this kind of equipment, will look very very pessimistically at the sort of cost that emerges when he has built in all these reliability features.

L. LØVBORG: Yes, but it should be considered that the design of electronic circuitry is getting less and less expensive because of the availability of integrated circuit elements with more and more built-in functions. Therefore, the instrument manufacturers can spend most of their design efforts on solving the reliability problems. I do not think that these problems are so expensive to overcome, they just require a lot of attention from the very beginning of the design phase. The real problem in being a manufacturer of geological field instruments such as portable gamma-spectrometers, I guess, is the fairly small market available for the sale of these instruments.

J.A. FERNANDEZ POLO: I wish to echo the question asked by Mr. Ostle and I would like to say that I am a total layman on this matter as far as detailed knowledge is concerned. I am, however, a daily user of such equipment, particularly because the people working with me are field staff. Obviously in certain field work a higher degree of precision is required, such as in air prospection or the radiogeometry of probes. In other aspects the tactics are important. Rather than perfecting the instrument to a high rate of discrimination and a high degree of feasibility, we are more interested in practical detection, because a sample can be taken by the prospector to a laboratory, where higher-precision equipment is used to work on it. What is of interest to us is cheap equipment and, I underline this aspect. It should be fairly long-lived equipment with greater or lesser sensitivity and high physical resistance. We have to accept a certain degree of error in measurement and we have to accept certain less sophisticated construction, particularly as this affects the price.

L. LØVBORG: I think that field measurements will be more and more important in the future, because we are prospecting in more and more remote areas. Although we will continue to take samples, it will take so long to get the results of the analyses that we must invest in equipment permitting field analyses. I do not agree that field measurements are less accurate and precise than laboratory measurements. You must remember that the moment you pick up the rock sample, you then have made a choice and the question is how representative is it for the field locality? This difficulty is to some extent avoided by making an in situ measurement, because of the fairly large area covered by the gamma spectrometer. Furthermore, if you pay the greatest attention to the radioelement ratios, the accuracy of these is not affected very much by the local topography. For instance, if you are near a rock wall you can still make accurate assessments of the U : Th ratio. I agree that the crystal-photomultiplier assemblies sooner or later will deteriorate in some way. Therefore, if you decide to make an investment in this kind of equipment you must also be prepared to invest in replacing the crystal-photomultiplier assemblies at certain intervals.

Y. SHIMAZAKI: I wonder what the upper temperature limit of the scintillation counters is. I am asking this because we will be having opportunities of carrying out surveys in tropical areas and in desert areas in Southeast Asia where the temperatures probably will be up to 50°C, at least over 40°C, and I am told that the reliability decreases rapidly in high temperature environments.

L. LØVBORG: I have no experience with high temperatures, but I think you are right in saying that it is more difficult to operate phototubes in high temperatures, as you will probably get a higher failure rate. I do not know

if anyone else has experience with scintillation counters in high temperature environments.

J. CAMERON: In November 1971 we had a consultants' meeting (on recommended instrumentation for uranium and thorium exploration) at the Agency. This subject was discussed and Mr. Matolín was one of our consultants. Perhaps he will recall what was said at that time.

M. MATOLÍN: It was agreed that there should be a minimum performance specifications limit for each instrument. Concerning the temperature limit we agreed that the temperature limit of gamma-ray spectrometers should be up to 40°C and possibly up to 50°C, but in this high temperature region there was the possibility of additional errors for any given accuracy of the instrument. So up to 40°C it should work normally. This was the general agreement of all the consultants.

Y. SHIMAZAKI: So that means there is nothing you can do in hot climates; is that the answer?

S.H.U. BOWIE (Chairman): This is my own experience too. The maximum that you can expect is 40°C and even then results are becoming less reliable than at lower temperatures. I am glad to hear that the Consultant Group agreed to this upper temperature limit.

D. OSTLE: Concerning this question of calibration in terms of the radioelement content of the material you are passing over, Mr. Darnley favoured this kind of calibration this morning for airborne work, and I can see that there is rather more advantage to gain from this type of calibration in airborne survey than in portable instrument work, because you are integrating over a very much larger piece of territory. But when you are considering the area of collection, if I may use lay terms, for the radiation from a rock surface, you are not looking at very much material and you are trying in effect, to give a grade, a tenor of a radioelement in quite a small area on the basis of an artificial standard. This is in effect simulating a dissemination of mineralization and is, very often, of course, very far from the actual circumstances that one is meeting in nature. Now do you think, Mr. Løvborg, that in fact this is really valid? Is it not going to give the geologist a false sense of security in having before him a reading which is expressed in terms of uranium when you may be looking in fact at a variety of mineralization which perhaps can affect this calibration? I very much doubt whether you would find the same uranium value for a narrow vein of pitchblende or uraninite as you would say from a few patches or a few crystals of uraninite in a pegmatite. Is this going to lead us into a false sense of security by trying to oversimplify the interpretation of these gamma-ray spectrometric results?

L. LØVBORG: This is a very important point. I said before that the geologist should not be concerned with the electronics of the spectrometer but he should definitely be concerned with the physical principles for the use of gamma spectrometers. He should know that such errors as you are talking about can occur and he should definitely not rely too much on concentration levels determined in situ – if he can see that the radioactivity is due to a few small crystals. I still think, however, that gamma-spectrometer results should be expressed in absolute concentration units, with reservations for inhomogeneity effects, as these units are in any case more informative than counting rates. If you give these figures and at the same time provide a description of the field locality – then you can avoid false interpretation.

M. MATOLÍN: This is the matter of comparison of gamma-spectrometry results. If you are trying to evaluate some small area you do not need any calibration values, but if you are going to compile a radiometric map of a larger area where probably more than one of these instruments has been used it is quite necessary, because there are difficulties with effectiveness of separate detection crystals. Among, say, five or six gamma spectrometers of the same type used in the same area there will be slight differences and only by this type of calibration we can overcome these difficulties.

D. OSTLE: I was not suggesting there should be no calibration but only whether the calibration in terms of radioelements was the right one to use. This brings us into the area of units, which is far beyond the scope of this meeting I am afraid.

EXPLORATION FOR URANIUM IN SANDSTONES
Geochemical, remanent magnetic, and sulphur-isotope applications

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Abstract

EXPLORATION FOR URANIUM IN SANDSTONES: GEOCHEMICAL, REMANENT MAGNETIC, AND SULPHUR-ISOTOPE APPLICATIONS.

For several years, forecasts of uranium requirements to meet projected demands for nuclear energy has indicated the need for intensification of exploration. Research is needed to improve ore discovery prospects and to develop a more favourable ore resource situation. Most of the uranium ore mined in the United States of America has been deposited at reduction-oxidation interfaces in fluviatile sandstones as a result of oxidation of pyritic carbonaceous facies. The ore-forming process produces large tongues of oxidative alteration which extend from the surface downward to the reduzate facies. Radioactivity and spotty mineralization at the surface reflect the presence of ore bodies at depth, but where these manifestations are absent other characteristics measurable in the outcrop of red or drab sandstones may be useful in evaluating favourablility for ore. Natural remanent magnetic properties, such as anomalous pole orientations or absence of remanent magnetism in Eocene or older fluviatile red-bed sandstones, may conceivably reflect relatively recent oxidation leading to ore formation at depth. The observed absence of magnetite and maghemite in presently oxidized sandstone can be attributed to reduction or leaching of these iron oxides by ore-forming processes. Unusually negative $\delta^{34}S$ values for sulphate sulphur in surficial gypsum, whole-rock samples or groundwater may indicate the presence at depth of ^{32}S-enriched pyrite with which uranium deposits are associated. Prudent and skilful appraisal and use of these properties coupled with a modest research effort to determine their limitations may yield rewarding dividends in extending the search for uranium into unexplored regions.

1. INTRODUCTION

In response to an awareness that development of new uranium resources would be necessary to fulfil raw material requirements between 1975 and 2000 for the growing domestic nuclear power industry, the Division of Raw Materials of the US Atomic Energy Commission formulated in 1966 a program of research which could be used to expand the scientific base for exploration for additional sources of uranium and for evaluation of discovery potential, should subsequent developments appear to require it. The objectives of the proposed program are essentially two-fold. First, the program provides for development of new knowledge, concepts, and techniques to facilitate exploration by industry in geological environments considered favourable on the basis of past experience, i.e., in fluvial sandstones. This effort would involve primarily development of additional geological, geophysical, and geochemical criteria, particularly in remote ground, that would point to the existence of as yet undiscovered uranium deposits. Second, it provides for improvement in capability to evaluate the prospects for existence and discovery of uranium resources in areas of the United States that are unexplored and about which virtually nothing

is now known regarding discovery potential. This involves among other things the particularly difficult task of developing some insight into the geochemical and geological circumstances under which uranium deposits could form in environments other than the well-known fluvial sandstones.

The formulation of this research program stemmed from the realization that the annual rate of discovery of uranium to provide for expected production requirements through 1980, while simultaneously maintaining an 8-year forward reserve, would have to approach in magnitude the reserves in each of nine of the ten major producing districts in the USA. The impending task, simply stated, was therefore one of discovering on a per year basis reserves equivalent to those of one major producing district. In spite of improvements in exploration technology and concepts, resulting from prior research, and industrial expertise in finding ore, a substantial effort to increase exploration capability seemed desirable.

The outlook today for meeting future domestic uranium requirements has not changed considerably and, therefore, the need still exists to develop geological and geochemical information and techniques that will improve ore discovery prospects. Moreover, the need to develop a more favourable long-term ore reserve situation is a world-wide problem [1], and improvements in exploration capability may be universally required.

In keeping with the goals of this Panel, this paper has a two-fold objective. Its first purpose is to describe the geochemical circumstances under which uranium deposits form in fluviatile sandstone, which is the most productive and favourable host for ore in the USA. This should make clear the considerations and reasons for proposing certain approaches to exploration. Its second aim is to set forth some criteria by which the favorability of sandstones may be judged. Although assessment of favorability is not in the strict sense a direct method or technique of exploration, such judgement should be equated in importance with the more routine mechanical approaches.

The paper draws in part from ideas generated in preparation of the USAEC research program. The approaches suggested here are, to the writer's knowledge, untested and perhaps novel. Their usefulness in exploration can be established only through a considerable amount of sampling, analytical work, and data gathering and analysis. Even with this accomplished, their ultimate value lies in applying them in conjunction with more direct exploration methods.

2. GEOCHEMICAL CONSIDERATIONS

In the major uranium-producing areas of the USA, uranium is confined chiefly to fluvial red and drab sandstones which, for the most part, occupy basins or basin-like depressions of fairly large areal extent. An important property of these sediments is the existence in them of two diametric geochemical environments or facies, one of which is chemically reducing and the other chemically oxidizing. The reducing environment, or reduzate facies, is characterized by the presence of organic matter and pyrite and is ordinarily grey in colour. The oxidizing environment, or oxidate facies, is typically represented by limonitic or hematitic red to drab sandstone.

Development of the reduzate facies during sedimentation is attributed [2] to rapid accumulation and burial of plant debris in arkosic sands and

muds deposited in alluvial fans and stream channels under humid semi-tropical conditions. These sediments spread basinward from orogenic highlands in gently aggrading river systems that meandered through broad savannahs before reaching the sea. Saturation of the sediments by groundwaters which became static and rapidly depleted in oxygen preserved the reduzate facies from oxidative destruction. The anaerobic conditions that prevailed were favourable for formation of H_2S and ensuing alteration of indigenous iron oxides to pyrite.

Eventual uplift of these sediments along the margins of basins permitted the entry of oxygenated meteoric waters. Where permeability and recharge were greatest, broad invasive zones or tongues of oxidation developed in the reduzate facies. In most of the major uranium ore districts, these tongues apparently extend basinward from the surface. Their development is clearly attributable to oxidation of pyrite and organic matter by oxygenated meteoric waters. The oxidized zone or oxidate facies formed in this manner is referred to by some authors as the "altered sandstone tongue" [3, 4], "barren interior" [5] or "geochemical cell" [6].

At the leading edge of the oxidation tongue, where it is in contact with the reduzate facies, is a rather narrow zone along which the oxidation potential (Eh) of the sediments changes rather abruptly. As a result, various metallic and non-metallic elements have accumulated there, the most important of these, from an economic standpoint, being uranium. Uranium is generally soluble in oxidizing environments, from which it is readily leached in aqueous solution, and insoluble in reducing environments, where it precipitates to form pitchblende deposits. Its localization at the redox interface along the edge of the oxidation tongue is therefore to be expected. Vanadium, molybdenum, copper, selenium, rhenium, sulphide sulphur and iron as pyrite are also concentrated there. These elements are normally deposited as low-to-intermediate valent compounds. The process of accumulation through cyclic reduction-oxidation and solubilization-precipitation, and factors affecting it, have been described elsewhere [7-9] and will not be elaborated here. The reduzate facies usually extends for a considerable distance beyond the redox interface, but ore is generally confined in most districts to a relatively narrow zone adjacent to the oxidate facies. The reduzate facies is referred to by some authors as the "unaltered sand or sandstone" [3, 4], "remote barren ground" [5] and "protore" [5, 6].

The redox interface is rarely straight or unswerving owing to differential transmissivity and rates of chemical interactions in various parts of the sandstone. The ore deposits, or ore rolls as they are called, formed at these redox interfaces are sinuous in plan and crescent-shaped or nearly so in cross-section. The ore bodies are relatively small targets, and exploration for them involves locating the interfaces by drilling in fence patterns from oxidate towards reduzate facies or vice versa. Two or more sandstone beds separated by mudstone lenses or beds may each contain an ore roll. These rolls do not necessarily overlie one another and must be located independently.

3. PROBLEM AREAS

Productive and potentially productive sandstones are those containing extensive reduzate facies. Sandstones in which this facies was never developed or in which it was completely destroyed during early diagenetic

stages are,by virtue of being chemically non-reductive, also essentially barren of uranium. Total destruction of the facies following mineralization may limit productivity to relatively stable oxidized remnants, e. g. carnotite deposits.

Surface radioactivity has been largely responsible for focusing early attention on the major ore-bearing areas, which subsequently were found to be substantially more productive at depth. In recent years, geochemical manifestations of ore have played an equally if not more important role in exploration, particularly in determining the location of redox interfaces. The drab limonitic, or sometimes bleached appearance of the oxidation tongues constrasts with the gray, pyritiferous character of the reduzate facies. The color change as well as mineralogical differences serve to guide drilling toward the chemical interface. In some districts, intensification of bleaching or of limonitic pigment in gossanous accretions is indicative of pyrite oxidation and hence symptomatic of a favourable environment for ore. In other districts, hematite replaces limonite, thus imparting an even more conspicuous hue to the oxidate facies, which is then more easily recognized in drill cuttings.

In some areas, interfaces can be observed between red hematitic and drab limonitic oxidate facies. The interfaces occur near ore and have the crescent-shaped traits of the contact between the ore roll and the oxidized sandstone. Their mode of formation has been described in an earlier paper [9]. It is believed that the hematite forms on dehydration of limonite as a consequence of aging or an increase in groundwater temperature. Where continuing oxidation has renewed the limonite zone, a pyrite-limonite-hematite progression results with each zone separated by a roll interface. The limonitization and hematitization process may be repeated many times as oxidation of the reduzate facies progresses basinward. Red-drab interfaces can be seen at the surface and in the subsurface in the San Juan Basin, New Mexico [10, 11] and have also been recognized in the Powder River Basin, Wyoming [12, 13] where they are closely associated with ore.

The contiguous association of limonitic and hematitic zones in sandstone is an important guide to ore in fluviatile sandstones of the western U. S., but its usefulness is not without qualification. Both limonite and hematite may originate in other ways [14-17] and their presence in sandstone is not necessarily related to oxidation of pyrite. Both may be deposited with the detrital fraction of sediments or result from alteration of iron-bearing silicates and oxides. It is conceivable that roll-like interfaces between limonite and hematite could form under these alternative circumstances, particularly if oxidation takes place below the water table, but the question is debatable. Obviously, where limonite-hematite rolls are accompanied by more specific indications of uranium mineralization, they serve as a useful guide to regional as well as local distribution of ore. In the absence of such indications they should be used with some reservation.

Hematite-limonite rolls are not commonly observed in sandstone outcrops although both hematite and limonite are common and widespread in these rocks. Unfortunately, no reliable way has yet been developed to determine whether hematite pigment in red beds was (a) deposited with the sandstone; (b) derived by dehydration of limonite; or (c) produced by interstratal alteration of iron-bearing minerals other than pyrite [18]. Also, there appears to be no way to distinguish between limonite pigments of different origins. Obviously, a method to distinguish

hematite, or limonite, formed on oxidation of pyrite from that having other origins would be a very useful tool for exploration and would facilitate evaluation of uranium resource potentials in unexplored areas. One possible approach will be considered here. The method makes use of the magnetic properties of red beds. Its application is, however, contingent on hematite being the dominant source of the remanent magnetic character of the sandstone.

Two other geochemical approaches to evaluating favourability of sandstone are also discussed. These involve mineralogical changes that affect the iron-oxide content and the sulphur-isotope composition of red or drab sandstone. All of these methods have the obvious advantages of being applicable to oxidized sandstone outcrops.

4. REMANENT MAGNETIC PROPERTIES

Magnetization of red-bed sandstone is attributed largely to some form of hematite which is formed and simultaneously acquires a stable chemical remanent magnetization (CRM) as a result of post-depositional alteration of iron-bearing minerals in the weathering environment. If two contemporaneous sandstone beds undergo a different oxidation history, e.g., early diagenetic formation of hematite as contrasted with oxidation of pyrite during a later geological period, they are likely to show a different remanent magnetization.

In very fine-grained sediments, detrital magnetic particles, including hematite, incorporated during sedimentation may become aligned by the earth's magnetic field and acquire a depositional remanent magnetization (DRM) [19]. However, under turbulent conditions in which coarser-grained, cross-bedded, fluvial sandstones are deposited, good alignment generally does not take place. Any detrital remanent magnetization lodged in the clastic iron-oxide grains is destroyed by chemical disturbances which alter the oxides to sulphides [18], and when the latter in turn oxidize, a stable CRM may develop in the ferric oxide products. Dehydration of limonite to hematite can also be a substantial contributor to remanent magnetization directions [19].

Coarse-grained red beds such as the ore-bearing sandstones containing predominantly inherited (detrital) hematite, magnetite, or other iron oxides may be identified by poor grouping of magnetic directions. On the other hand, a relatively high degree of magnetic polarization is to be expected in red beds deriving hematitic pigment from later alteration of iron silicates or pyrite. Since pyrite oxidation is a fairly recent geological event in the ore-bearing sandstones, the CRM directions of these red beds may differ from the CRM directions of contemporaneous beds deriving their red pigment primarily from iron-silicate alteration during an earlier diagenetic stage. A distinction may be made between the two CRM modes if the geomagnetic fields existing at the time of development of CRM had different orientations.

Reversals of the geomagnetic poles are common during certain periods of geological history [20], and sandstone units, of approximately the same age, developing DRM or CRM during these periods will reveal magnetic zone reversals that parallel bedding. The zones may cut across dissimilar color, textural, and lithologic facies. In contrast, oxidation of pyrite in these

same sandstones could be expected to produce uniformity of magnetization throughout the vertical extent of each bed inasmuch as this oxidation sweeps through a sandstone in nearly vertical fronts along the hydrological gradient. Under the latter circumstances any magnetic variations, if they do exist, would be observed to occur laterally rather than vertically, i. e., the magnetic time lines might coincide with the more nearly vertical redox interfaces in the sandstone. Whether vertical magnetic time lines do indeed exist has probably not yet been established, and their existence is therefore questionable. Sandstones that accumulated during long periods of consistent paleomagnetic poles, e. g., from late Jurassic to late Cretaceous [21], also may develop vertically uniform CRM or DRM properties. However, unless such sandstones derived their hematitic pigment from oxidation of pyrite, they are unlikely to develop vertical magnetic time lines. Furthermore, they may show magnetic polarity that differs from that of contemporaneous sandstones in which a CRM evolved later as a result of pyrite oxidation.

Pliocene and younger coarse-grained red beds appear to have no stable magnetization, whereas Eocene and older beds do [22]. This suggests that CRM may develop several million years after deposition. Absence of CRM in coarse-grained fluviatile red beds of Eocene age or older could therefore be taken as evidence of post-Eocene hematitization. Because pyrite oxidation in Mesozoic and Eocene host sandstones in the USA appears to have occurred fairly recently in many uranium ore districts, these rocks should be devoid of CRM where they are favourable for uranium and should possess CRM where they are not. Generally speaking, the absence of stable remanent magnetization in pre-Pliocene coarse-grained fluviatile oxidized sandstones should be taken as a favourable indication of a geochemical evolution conducive to uranium deposition.

To the writer's knowledge, no investigation has been undertaken to determine whether remanent magnetic properties of rocks are applicable to uranium exploration or resource potential evaluation, although a project to establish this had been proposed in 1966 by the Division of Raw Materials of the US Atomic Energy Commission. From a conceptual standpoint, remanent magnetism appears to be fruitful area for study.

5. MAGNETIC IRON-OXIDE RELATIONSHIPS

It is obvious from the foregoing discussion that the pigmenting iron oxides, namely geothite and hematite, in the oxidate facies of sandstones may originate by mechanisms other than the oxidation of pyrite and that only when both oxides occur contiguously to form roll-like interfaces is their presence a useful guide to uranium exploration. It is also apparent that the remanent magnetic characteristics of the iron oxides in sandstone offer some promise of providing useful information. Still another approach to evaluating the favourability of red beds for uranium involves determination of the abundance of ferrimagnetic fractions (magnetite and maghemite) in sandstone. The rationale for this follows.

Magnetite is delivered from igneous and metamorphic rocks to sedimentary environments in a relatively unaltered state [18]. Its fate in sandstones is dependent largely on the extent of oxidation or reduction within the host rock. Under oxidizing conditions magnetite alters to

limonite, hematite, or maghemite [33], and under reducing conditions it is readily destroyed [18, 24, 25]. Maghemite evidently forms from magnetite containing trace amounts of water (0.2-0.7% H_2O), whereas hematite forms directly on oxidation of non-hydrous magnetite [26]. Maghemite is metastable, breaking down to hematite at 200°C or above. Hematite seems to be the dominant oxidation product in red beds, while maghemite is only a minor constituent [18].

In spite of its tendency to oxidize, which causes increasingly greater replacement by hematite in successively older red beds [18], magnetite persists in detectable quantities even in Paleozoic sediments [24, 25]. In the uranium-bearing Morrison formation (Jurassic), magnetite, or grains containing enough magnetite to be attracted by a hand magnet, constitute about 5-10% by weight of the total heavy mineral fraction of the sandstone [27]. In the Shirley Basin, Wyoming, magnetite occurs in unaltered (unoxidized) sand in significant amounts and is largely removed from altered (oxidized) sand [3]. Similarly, magnetite is observed in the Gas Hills, Wyoming, in the reduzate facies away from ore, but has apparently been destroyed in the ore zone as well as the alteration tongue [5]. Since magnetite is evidently dissolved by acid waters formed in a reducing environment [28], its destruction in ore rolls and its relative scarcity in the oxidated tongue can probably be attributed to formation of acidic solutions during oxidation of pyrite.

It may be concluded from the foregoing that magnetite is partially altered but not necessarily completely destroyed by oxidation during red-bed formation. In the presence of carbonaceous matter its oxidation is evidently inhibited. Moreover, in the reduzate facies, much of the indigenous magnetite probably alters to pyrite through interaction with bacteriogenic H_2S; however, evidently not all of it is so affected. Oxidative alteration of the pyritiferous sandstone causes further removal by acidic solutions. Consequently, red-bed sandstones in which pyrite is the source of the hematitic iron may be largely devoid of magnetite. Sandstones deriving hematite by other mechanisms can be expected to contain significantly more magnetite inasmuch as the destructive processes do not appear to be as effective. Since the chemical conditions associated with deposition of uranium in roll deposits seem to have the tendency to destroy magnetite and presumably also maghemite, absence, corrosion or reduction in quantity of these minerals may be a favourable sign. Complete destruction may not necessarily occur. It is possible to arrive at the same conclusion with respect to drab-bedded (limonitic) sandstones.

The ferrimagnetic mineral content of sandstone can be determined directly with the aid of a hand magnet, which greatly facilitates inspection of rock outcrops and drill cores. Generally speaking, such magnetic material is assumed to be magnetite. Since maghemite may also form by dehydration of lepidocrocite at 200-400°C, and perhaps at lower temperatures given more time, it may be desirable to distinguish between magnetite and maghemite. Absence of maghemite would rule out the possibility that hydrous iron oxide formed on oxidation of pyrite had dehydrated to maghemite. Under the latter circumstances, the presence of maghemite would not be an unfavorable indication. However, inasmuch as the origin of the lepidocrocite would most likely not be known, not much can now be gained from this line of reasoning. Hence, the absence of a magnetic fraction in red-bed sandstone is much more diagnostic.

Determinations may also be made with a magnetic susceptibility bridge. The values obtained are considered to be directly related to disseminated magnetite. The use of a bridge for locating areas favourable for uranium deposits has been suggested on grounds that (a) magnetite was originally uniformly distributed within the host rock, (b) uranium-bearing solutions had destroyed magnetite, and (c) magnetite is present under conditions unrelated to uranium mineralization [29]. Magnetite contents as low as 0.001% appear to be detectable [29].

6. SULPHUR-ISOTOPE RELATIONSHIPS

The possibility of identifying, with the aid of sulphur-isotope data, the source of the sulphur in various natural sulphur-bearing substances provides an opportunity for utilizing sulphur-isotope analysis as an exploration tool. Moreover, there is now a substantial amount of information on sedimentary sulphur isotope ratios with which new data may be compared.

It is evident from the typical examples of isotopic data shown in Fig. 1 that different types of sulphide deposits have perceptibly different sulphur-isotope compositions. Particularly noteworthy is the conspicuous difference in the position and range of values characteristic of sulphides from magmatic hydrothermal deposits on the one hand and sandstone-type uranium ore deposits on the other. Of the five given examples of magmatic origin, two, namely Schwartzwalder and Marysvale, are uranium ore deposits.

It has been shown [30] that the pyrite in the reduzate facies of red-bed sandstones is enriched in ^{32}S relative to ^{34}S and that this enrichment is characteristic of bacterially derived sulphide. In general, biological processes tend to concentrate the lighter isotope in sulphides and the heavier isotope in sulphates. This is manifest in the analytical data by higher $^{32}S/^{34}S$ ratios and increasingly negative $\delta^{34}S$‰ values of S^{2-}. Ordinarily, a broad spectrum of highly negative $\delta^{34}S$ values sets the biogenic sulphides in red-bed sandstones apart from other genetic types.

From the mass of isotopic data now available, it has become evident to the writer that the mean $\delta^{34}S$ values reported for sulphide deposits, although perhaps being no more significant than the individual values or the composite range of such values, provide a better basis for distinguishing groups of sulphides of biological origin. This is well illustrated by data (Fig. 1) obtained on samples from the Gas Hills area, Wyoming.

From the published data [31] on these deposits it is evident that in spite of the considerable overlap in $\delta^{34}S$ values between syngenetic-diagenetic sulphides and epigenetic sulphides, the mean values for these two groups of sulphides differ appreciably. There may be several reasons for this. One explanation hinges on the experimentally confirmed fact that if the rate of sulphate reduction is comparatively rapid, only slight isotopic fractionation occurs, whereas at slower rates fractionation is considerably greater. From this it may be concluded that bacterial activity, and sulphate reduction, is considerably lessened in the epigenetic environment. Another reason for the difference may be the manner in which epigenetic deposits form. From the foregoing account of uranium

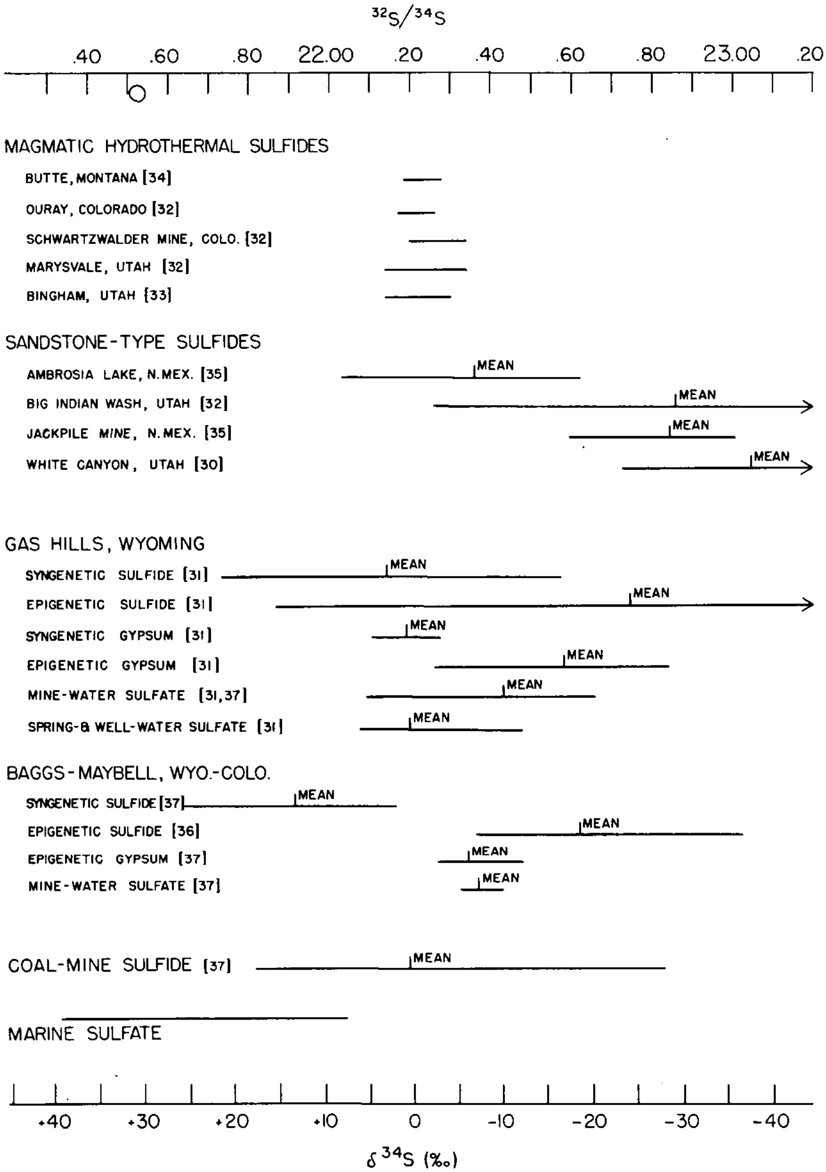

FIG. 1. Ranges and mean values of sulphur-isotope abundance data for various sulphides and sulphates grouped according to source.

ore-roll formation, it is evident that repeated cycles of oxidation-reduction occur and that these involve transformation of S^{2-} to higher valence states and re-reduction of these higher states to sulphide sulphur. Since each cycle tends to enrich sulphide in ^{32}S, the result is a gradual overall enrichment in epigenetic sulphide of the ^{32}S isotope.

The data (Fig. 1) on the Maybell district, Colorado. also show a considerable difference between the mean $^{32}S/^{34}S$ ratios of syngenetic and epigenetic sulphides, but in this case there is also a conspicuous disparity in the ranges of the two sets of values, thus emphasizing the genetic difference.

For comparison, $\delta^{34}S$ values for syngenetic-diagenetic pyrite from numerous coal deposits (unpublished data on 71 samples) are shown. The values are strung out over a considerable range but somewhat on the heavy side of epigenetic sandstone-type pyrites. Here too, however, the $\delta^{34}S$ mean is considerably less negative than the mean for epigenetic sulphides and much closer to the mean for syngenetic-diagenetic sandstone-type sulphides. This is to be expected inasmuch as syngenetic-diagenetic pyrites in coals and in carbonaceous sandstone environments are probably formed in a similar manner.

For exploration purposes, comparison of mean $\delta^{34}S$ values for sulphides would be very informative, but such samples are not ordinarily obtainable in the outcrop and are usually acquired only by drilling into the reduzate zones in sandstones. Instead, examination may be made of the oxidation products, such as calcium sulphate, which are more stable in surface exposures. The problem here is to distinguish between sulphate which is indigenous and that which is extraneous, but this is not absolutely necessary provided one is aware of the limitations involved in interpreting the data. An example of the kind of reasoning that may be applied follows.

Epigenetic gypsum from the ore-bearing host rock in the Gas Hills areas is enriched in ^{32}S whereas syngenetic gypsum shows $\delta^{34}S$ values that fall on the heavier side (Fig. 1). Sulphate sulphur extracted from mine waters also shows a $\delta^{34}S$ mean that is lighter than the mean for syngenetic gypsum, but the value is heavier than the mean for epigenetic gypsum. The isotopic mean for syngenetic gypsum is similar to the mean for syngenetic pyrite, and the isotopic mean for epigenetic gypsum is closer to the mean value for epigenetic pyrite than it is to the mean for syngenetic pyrite. The $\delta^{34}S$ mean for sulphate in the water samples can be explained as resulting from mixing of sulphate derived from both epigenetic and syngenetic pyrite. In contrast, sulphate in waters from various wells and springs in this area yields a lower $^{32}S/^{34}S$ mean ratio which is close to the mean for syngenetic gypsum and pyrite.

The main point to be derived from the data presented here is that the sulphate sulphur associated with the Gas Hills uranium deposits has a more negative $\delta^{34}S$ average composition than either the syngenetic sulphide or sulphate in the area. It is reasonable to conclude that this enrichment in ^{32}S results from sulphate added to the environment by oxidation of epigenetic sulphide which is characteristically lighter in isotopic composition than syngenetic sulphide. A parallel situation exists in the Baggs-Maybell district (Fig. 1). It should be possible therefore to use sulphate samples to identify areas where ^{32}S enrichment has taken place, thus revealing geochemical conditions favourable for uranium deposition. However, since there is no characteristic mean value for syngenetic sulphides

as a group, or for epigenetic sulphides, or sulphates associated with these sulphides, considerable sampling may be required to establish the norms in an unexplored area. The relative ease of acquiring samples from outcrops or surface trenches, etc. make this a manageable task. Moreover, because a large number of samples can be combined and representative portions analysed to obtain mean $\delta^{34}S$ values, analytical costs are reducible to justifiable levels. Where gypsum is not available, whole rock samples or surface drainage and spring water may provide sufficient sulphate.

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DISCUSSION

S.H.U. BOWIE (Chairman): Thank you very much, Mr. Adler, for this extremely interesting approach to the problem of identifying areas favourable for uranium exploration. The sulphur isotope technique is one of great interest to me and I wanted to ask you whether you have thought of combining this in any way, for example, with $^{18}O:^{16}O$ ratio work?

H.H. ADLER: To my knowledge, no work has been done on oxygen isotopes related directly to the uranium exploration problem. There is, of course, a considerable literature on $^{18}O:^{16}O$ ratios, largely on waters and other materials. The problems of interpretation appear to be tremendous because, unlike sulphur which tends to be isotopically more stable, oxygen equilibrates easily with its environment. I understand that if a solid sample is put in an acqueous solution, the oxygen atoms from the solid material will exchange with the oxygen in the liquid material, so that if the liquid environment changes through geological time, this change may also gradually be reflected in the mineral material exposed to the liquid. That makes for the sort of values that become largely uninterpretable or misleading in terms of geological processes and the origin of the materials. I understand that oxygen in pitchblende has not yielded information of any significance. This is similarly true with the oxygen associated with sulphate sulphur. One could look at that oxygen and attempt to tell when it was added to the sulphur to form the sulphate, but I believe it has been established that sulphate oxygen equilibrates at least to some extent with oxygen in water, so that the isotopic composition of the sulphate oxygen may continually be changing with time, just as the composition of the water changes.

J. CAMERON: Could you give us some idea of costs on the type of research work you are doing?

H. H. ADLER: Initially, the work that was done on sulphur isotopes related to the uranium problem was under contract to Dr. M. L. Jensen at Yale University and subsequently at the University of Utah. That research began about 1958 and terminated about three years ago, so it was a rather long-term thing—we got a tremendous amount of useful data out of it. And I think the average cost per year must have been something on the order of \$35 000 - \$40 000. However, one does not have to go that route any longer. Isotopic analyses are now available commercially. They are not generally available, but there is at least one company I know of in the United States that will provide isotopic data on sulphate and sulphide samples at a cost of \$60 for analysis of the sulphate sulphur and \$40 for analysis of the sulphide sulphur. So that any individual who conceives of a project to which sulphur isotope data would be applicable need only formulate that research project, collect his own samples, submit these commercially for analysis and draw his own conclusions. To initiate a research project utilizing one's own equipment involves the tremendous logistics and expense of setting up a mass spectrometer. These instruments must now cost \$80 000 or thereabouts, and their maintenance is, of course, a very costly and delicate thing, so I would not accept that as a reasonable alternative to getting your sulphur isotope data commercially at this time.

J. F. DAVIS: You mentioned the importance of the mean values versus range. This, of course, would necessitate, I presume, a rather large number of samples. Would you have any idea of the minimum number of samples that it might require to obtain a satisfactory result of any one project.

H. H. ADLER: This is always a difficult question to answer. You can always add a little more data and your values may change, but I think we have something on the order of 30-40 sulphide samples representative of these syngenetic and epigenetic environments. For the coal deposits – I have also indicated the general isotopic composition of pyrite in coal – this represents something on the order of 75 samples. But having established some norms for comparing with new samples, I would say that five or six sulphate samples from any given outcrop would give you a clue; e.g. if you found that the sulphur isotopic composition indicated enrichment in ^{32}S that was anywhere near the upper range of the biogenic sulphides associated with uranium ores you would have a good indication of favourability. In general, that type of indication would, I think, be satisfactory. Combining samples will also reduce costs and accomplish almost the same objective. How do we find sulphate samples in outcrop? You do not have to look for the gypsum. Chemical determinations may tell you that there is a small per cent of sulphate in the sandstone rock. What that might involve then is taking the bulk sandstone rock and leaching out the sulphate sulphur in hot, slightly acid (hydrochloric) solutions or by some other acceptable procedure and then precipitating the sulphate with barium chloride to form barium sulphate.

J. A. FERNANDEZ POLO: Can these ratios be very much altered by the inclination of the various strata?

H. H. ADLER: You are implying that there may be a different isotopic composition of sulphur associated with severely inclined deposits as contrasted with gently inclined deposits, and I would say I can see no geochemical reason for this being the case. A physical factor such as the dip of a bed would appear to have no direct effect whatsoever on changing the isotopic

composition of the sulphide sulphur which is in that bed and which is already an intrinsic part of that bed, nor of changing the isotopic composition of the sulphate sulphur derived from that sulphide sulphur. I think perhaps other factors of much more importance are the proximity of an evaporite deposit which may introduce, perhaps through surface erosion, large volumes of sulphate sulphur of an entirely different origin into these fluviatile sandstones. Since the sulphur in evaporite sulphate is usually very heavy isotopically, this would then tend to blend in with the isotopically lighter sulphate sulphur and give you some median value which might completely obscure the isotopic evidence of sulphate derived from epigenetic biogenic pyrite. When you collect your samples you most be cognizant of such a possibility. None of these techniques is a panacea; you cannot just blindly use them. You have to familiarize yourself with the whole spectrum of isotopic possibilities and then use that data intelligently in the light of all the various factors and parameters that can cause confusion or change situations.

M. KETOLA: Do you know what the order of magnitude is of the variation in the intensity of remanent magnetism between different sandstone beds, and what, if any, is the difference in susceptibility?

H. H. ADLER: The measurements that are made are generally not intensity measurements. This is a very complicated subject and it needs someone with a great deal of specialized skill and understanding to go into it thoroughly. Some very detailed technical books have been written on the subject of magnetism and I do not pretend to understand them nor is an understanding absolutely necessary for utilizing the resulting data in exploration. You can see from the available data certain applications to exploration problems. Very simply, what is measured are vectors, and these vectors are presumably aligned more or less parallel to the earth's magnetic field at any particular time during geological history. The magnetic field changes considerably in its direction and it does so unpredictably. For example, during Permian time, changes have been detected over close time intervals, that is over periods of a million years or so. Measurements are somewhat statistical and from these a scattering of points is plotted and a mean direction is determined. Pole reversals can also be measured. There are other periods of geological history when a magnetic field has been relatively stable, so one has to know from the data at hand what the magnetic declinations are for any particular time period with which one is concered. For example in Jurassic time a magnetic declination points in a certain direction. Therefore, hematite formed in red beds at that time would be expected to give you that vector. But suppose that the hematite in the Jurassic beds was formed in Eocene time and that the earth's magnetic declination was in a different direction. Then you could look at hematite in a Jurassic red bed and presumably determine whether that hematite was formed in Jurassic time or in Eocene time.

Because these roll ore deposits are relatively recent, probably formed within the last million years or so, and since it takes hematite a certain amount of time to pick up its magnetism after it is formed, it may take several tens of millions of years for this magnetic vector to form in hematite associated with these rolls. Since the hematite that is associated with the oxidation of these roll ore deposits is very recent, it may exhibit no magnetic directional properties. In a Jurassic formation in which ore

deposits were formed within the last few million years, you will find that the hematite associated with ore roll formation is the result of pyrite oxidation and therefore probably has no magnetic vector. This absence of magnetic vector should immediately make you suspect a very recent age of formation of that hematite and therefore associate it with pyrite oxidation. Whereas if you had normal Jurassic vectors in the hematite you could assume perhaps that oxidation had already been completed in Jurassic time and that therefore there is not very much possibility of ore rolls being present. This is particularly true where hematite was incorporated in sandstone that never had much if any reducing character. Red-bed geologists categorize red-bed sandstones according to many different genetic types and one of them is a primary depositional type. Obviously this type of red is of no value as an indicator of uranium mineralization.

M. KETOLA: I agree with Mr. Adler that in remanent magnetism measurements of rock samples we usually determine the components of remanent magnetization and calculate according to them the total intensity of remanence, its inclination and declination (and Q-value). But if the intensity of remanence is strong, you can make a measurement by ordinary magnetometer or Förster Oerstedmeter (which we use in our laboratory) – if it is weak you need controlled circumstances and an astatic magnetometer or a spin magnetometer. If the intensity of remanence is strong, it is easier to make routine determinations and you can use simpler instruments.

SOME ASPECTS OF GEOCHEMICAL SURVEYS FOR URANIUM

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Abstract

SOME ASPECTS OF GEOCHEMICAL SURVEYS FOR URANIUM.

A review of the geochemistry of uranium in the supergene environment is given in relation to geochemical prospecting. The effects of particular chemical factors complicating the interpretation of prospecting data are discussed, including those of bicarbonate sulphate and chloride complexes, organic material, sesquioxide complexes and phosphate precipitates. Present sampling and analytical methods are discussed and conclusions drawn as to the relative merits of stream-water, stream-sediment and soil sampling. Future progress is believed to rely on adequate dissemination of the results of geochemical surveys and on a better understanding of interpretative problems.

1. INTRODUCTION

Because of its economic and strategic importance, basic uranium geochemistry has been the subject of a voluminous literature. It is perhaps surprising, therefore, that with a few notable exceptions, those concerned with the search for uranium have only in comparatively recent years begun to make comprehensive studies of the value of geochemical prospecting methods. Published case histories of geochemical surveys for uranium are still relatively uncommon, yet in the short term, it is in this field of prospecting activity (if radon measurement is included) that there would seem to lie the best likelihood of discovering new uranium fields and individual deposits which are not amenable to detection by radiometric methods. Even in areas in which deposits remain to be found by traditional means, the geochemical survey can represent a powerful tool in improving the economics of search. For instance, Dyck [1] concluded from the study of a 500 square mile test area in the Beaverlodge area of Saskatchewan that the regional survey, employing radon and uranium in surface waters and uranium in stream sediments, reduced the uranium search area roughly by a factor of 10 and isolated mineralized zones of 3-10 square miles. Ostle and co-workers [2] demonstrated that a primary geochemical reconnaissance conducted in a 2500-km^2 area in northern Scotland would have identified the most favourable prospecting areas for non-refractory uranium occurrences, by showing the relative distribution of uranium between resistates in stream sediment samples and surface water.

The methods employed for sample collection and analysis are now well documented and the main problems facing the uranium exploration geochemist are the choice of sampling media to meet particular circumstances and the interpretation of results. The distribution and concentration of uranium in the weathering cycle is dependent on a large number of chemical and physiographic factors. These are generally understood, but an attempt is made later in this review to discuss the chemistry of the more important of them,

since improvements in the interpretation of data, for which a proper understanding of the underlying processes is a concomitant, are likely to be the most effective means of progress towards more effective application of geochemical prospecting techniques.

2. SAMPLING AND ANALYSIS

Uranium geochemical surveys, like those for other metals, can be divided broadly into two categories: regional reconnaissance and detailed "follow-up", the "strategic" and "tactical" prospecting defined by Grimbert [3]. Consideration of the most common modes of uranium occurrence in exploitable deposits, and the almost invariable association of the uranium minerals with reactive minerals, suggests that water must be the most important transport medium for uranium in the supergene environment. Stream sediments and soils become important media in regions in which the uranium occurs in minerals resistant to weathering, e.g. thorian uraninite such as occurs in the Indus River alluvium, and in arid areas or those in which rainfall is markedly seasonal. It has been demonstrated [1, 4] that the uranium dispersion train in water is longer than that in stream sediment in the environments of the United Kingdom and Northwest Canada; but the variety of factors which can influence dispersion emphasizes the importance of the initial step in all geochemical surveys, namely the orientation study to determine the most favourable media to be sampled. A major consideration relating to the use of stream sediment samples, irrespective of their potential for uranium discovery, is the information they provide on the distribution of other economic minerals and of associated elements of possible value in interpretation of the geochemical data.

It is also at this stage that a decision must be taken on the fraction of sample to be analysed when stream sediment sampling is incorporated in a survey. The fraction is determined by field tests and may vary in different circumstances from minus 60 BSS mesh [1] to minus 150 BSS mesh [3].

Another major decision to be taken prior to the start of routine sampling is that of determining whether samples should be analysed in the field or at a home laboratory. Again, practice varies and will depend on the analytical method to be employed, the availability of local facilities and personnel and the requirements of the field geologist in relation to "follow up" investigations and seasonal deadlines. The commonest practice at present is to undertake all analyses at a home-base laboratory, although field laboratories have proved successful in some circumstances [3]. It is patently necessary to use a central facility for uranium analysis by the recently described method of delayed neutron measurement [2], which requires access to a reactor, while the multi-element analysis of stream sediment samples is most effectively conducted on automatic spectrometers which require laboratory conditions for their operation. Nevertheless, an in-field facility can provide considerable advantages for day-to-day operations in remote areas. Attempts have been made, with varied success, to develop "stream-side" analytical systems and there would seem to be scope for further development of rapid, portable or transportable systems to augment the major throughput of samples from large systematic surveys by laboratory-based equipment. Table I summarizes analytical techniques currently available.

TABLE I. ANALYTICAL TECHNIQUES CURRENTLY AVAILABLE[a]

Method	Field application	General remarks
Fluorimetric		
(a) Direct	Yes	Subject to matrix effects, suitable for water
(b) With chromatographic separation	Yes	Specific, time-consuming, wide application
Gamma spectrometry	Limited use	Suitable for materials in secular equilibrium, not suitable for alluvium or soils
X-ray fluorescence	No	Subject to matrix effects but has advantages if multi-element determinations necessary
Colorimetric	Yes	Time-consuming, imprecise at low concentrations
Neutron activation		
(a) Radiochemical analysis of fission products	No	Very sensitive and specific, but requires special equipment and staff; slow
(b) Delayed neutron measurements	No	Rapid, no matrix effects, suitable for unskilled operators or automation

[a] Taken from Ostle and co-workers [2].

The final selection of the most suitable analytical system will be based on a combination of economic and technique performance factors and must take account of the need to measure parameters other than the uranium content of samples (pH, Eh, conductivity, etc.), for interpretative purposes. Checks on sampling and analytical reliability should ideally be incorporated in the system.

The detection limits of analytical procedures employed should be sufficiently low to allow detection of significant contrast between background and anomalous levels of concentration. Limits will therefore differ, depending on the type of sample examined, but values to be expected from stream sediment and soil samples are well above the detection limit of the common analytical techniques currently employed. On the other hand, the background level for surface waters in many regions approaches the detection limit of some of the techniques (unless additional concentrating steps are included in the system) and may be below that of others. For instance, the most economical and convenient procedure for the determination of uranium in water, by the delayed neutron method, produces a detection limit of approximately 1 $\mu g/l$, which is higher than the background in at least two major regions surveyed in the United Kingdom and roughly twice that of stream and lake water samples in Saskatchewan [1]. However,

geochemical prospecting in the UK has shown this limit to be adequate to ensure the detection of anomalies related to discrete uranium concentrations. Thus, 70% of stream water reconnaissance samples containing uranium in excess of 3 $\mu g/l$, in an area in northern Scotland, were shown to lie downstream from uranium-bearing structures.

3. INTERPRETATION OF DATA

Rapid visual inspection of results may in many cases be adequate to identify anomalous uranium concentrations which merit immediate investigation by more detailed sampling, radiometric and geological inspection, provided that, in the case of water samples, there are no chemical features of the water on the basis of which the interpretation should be modified. Subsequent, more thorough interpretation involves plotting the results, for their inspection, in relation to local topographic relief, geology and hydrogeochemistry. The application of statistical analytical procedures to determine population trends may have significance on the local or regional scale. The uranium content in water may be merely a function of the maturity of the water in the hydrological cycle and the activity of certain anionic complexes. Thus in the Orcadian cuvette of Scotland and in the Permo-Triassic basins in England, the clarke of uranium in spring water is higher than the corresponding value in stream water. To distinguish anomalies of this type from those related to mineralization, simple and multiple correlations between uranium and major elements dissolved in the water may have to be performed. Regression analysis of uranium on certain major elements is particularly useful in this respect and the relationship of uranium to the activity of the most important anionic complexes is discussed below. The effects of organic matter and hydrous oxides of iron and manganese are also considered.

Some of the more important factors influencing the transport and redeposition of uranium in the weathering cycle, and therefore having a bearing on the interpretation of geochemical distribution patterns, are bicarbonate, sulphate and chloride complexes, organic matter, hydrous oxides of iron and manganese and phosphate precipitates [5].

4. TRANSPORT IN SOLUTION

4.1. Bicarbonate complexes

Since carbonate is one of the most important constituents of water influencing the complexing of uranium in solution, an understanding of the mechanism of its introduction is desirable. Calcite is sparingly soluble in pure water but considerably more so where the system has contact with a reservoir of carbon dioxide. The solubility is also temperature dependent. The main sources of carbon dioxide are the atmosphere, with an average of 0.03%, and soil air in which concentrations are variable but may reach 10% CO_2. Volcanic exhalations may also be important sources in some areas. Provided that rainwater falling on calcareous rocks penetrates the latter quickly, it will dissolve less carbonate than water remaining in contact with the atmosphere, where the CO_2 used in producing $Ca(HCO_3)_2$

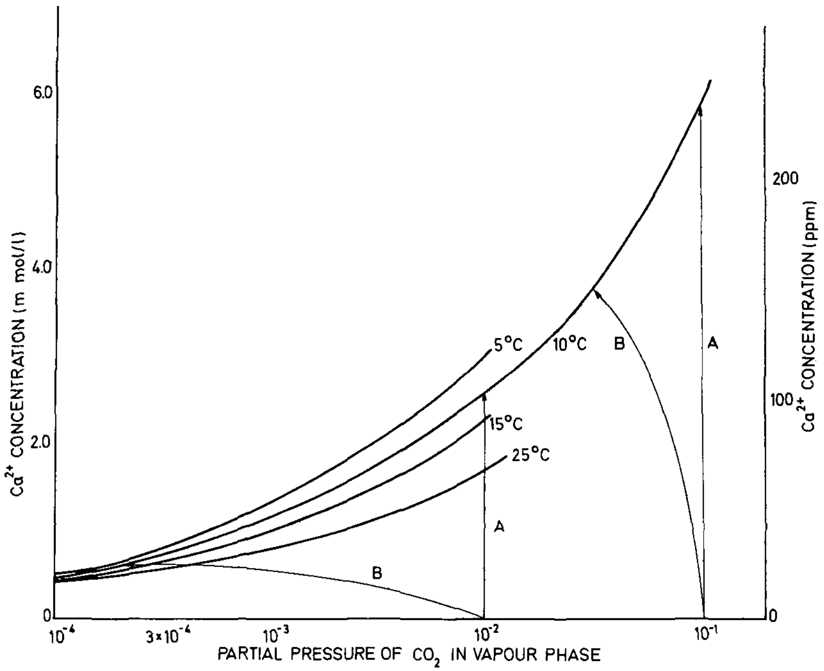

FIG.1. Derived and modified from Holland and co-workers [6], this figure shows the changes in composition of carbonated water during equilibration with calcite at various temperatures in the presence (A) and in the absence (B) of a vapour phase. Consider water having equilibrated with a vapour with a particular partial pressure of CO_2 being brought into contact with calcite. Thus, depending on whether it remains in contact with the vapour phase or is immediately removed from contact, the composition of the resulting aqueous phase will be represented by path A or path B.

is replenished. The temperature dependence of the reaction should lead to greater dissolution of limestone in winter than in summer. However, biotic activity, being greater in summer, leads to a higher level of CO_2 in soil air and so to more intense dissolution of carbonate and a greater concentration of bicarbonate in groundwater. These relationships are summarized in Fig. 1, which is modified from Holland and co-workers [6].

Thus the season, the relative proportions of exposed and soil-covered calcareous rock, the temperature and the proportion of surface water to groundwater will affect the bicarbonate content of water in an area. Other factors affecting the solubility of carbonate are the presence of other ions, e.g. SO_4^{2+} and Mg, and base exchange with saline waters.

Szalay and Samsoni [7] have shown by laboratory leaching experiments on natural rock powders that increasing the bicarbonate content of the leach water increases the proportion of uranium dissolved, but that equilibrium is rapidly achieved. This has also been deduced from geochemical investigations in a Triassic area of the English Midlands. The groundwater is hard and contains anomalous concentrations of uranium in solution. Statistical analysis indicates that a very strong degree of positive correlation exists between the alkalinity (mg $CaCO_3$/l) and the uranium content of surface

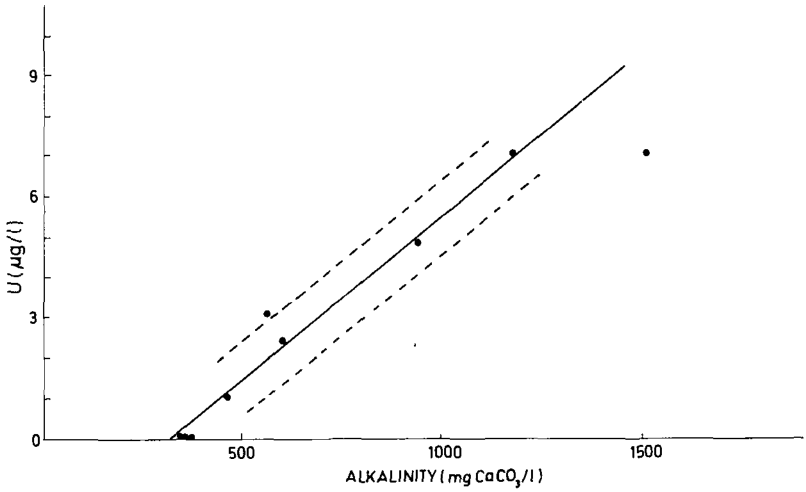

FIG.2. Plot of uranium vs. alkalinity, in a group of bore-holes interspersed over an area of two square miles.

waters and borehole waters. The gradient of the regression lines for both sets of data are closely similar but the axial intercepts are different, reflecting the greater alkalinity of the groundwater. There is considerable re-change of the surface streams by groundwater in the area, the lower alkalinity of the surface water reflecting the equilibration of the water with atmospheric levels of CO_2. The uranium contents are not significantly depleted compared with those of groundwater.

This feature of correspondence between uranium and bicarbonate is illustrated by data from boreholes which intersect the same aquifer in a small part of the area. The rocks do not exhibit anomalous radioactivity and rock samples contain no more than 4 ppm U, but there is nevertheless a strong correlation between alkalinity and uranium. This is illustrated in Fig. 2.

Hostetler and Garrels [8] have discussed the behaviour of the U-O_2-H_2O-CO_2 system as it applies to natural conditions and a comparison of Fig. 4 with Fig. 3 shows the enormously expanded stability fields of the soluble uranium species, in this case of a surface stream in contact with excess $CaCO_3$ and at equilibrium with the partial pressure of CO_2 in the atmosphere, when compared with a carbonate-free environment. The tri- and bicarbonate complexes are very stable and very soluble. This situation is well demonstrated by hydrogeochemical data from Caithness in northern Scotland, an area underlain by Old Red Sandstone, calcareous and bituminous sandstones and shales containing thin limestones. Uranium mineralization occurs in phosphatic horizons in the shales and in carbonate and phosphate vein fillings. Surface waters are hard and their uranium content high, dispersion trains from the uranium occurrences being long. There is comparatively little contribution of uranium from stream water to stream sediment.

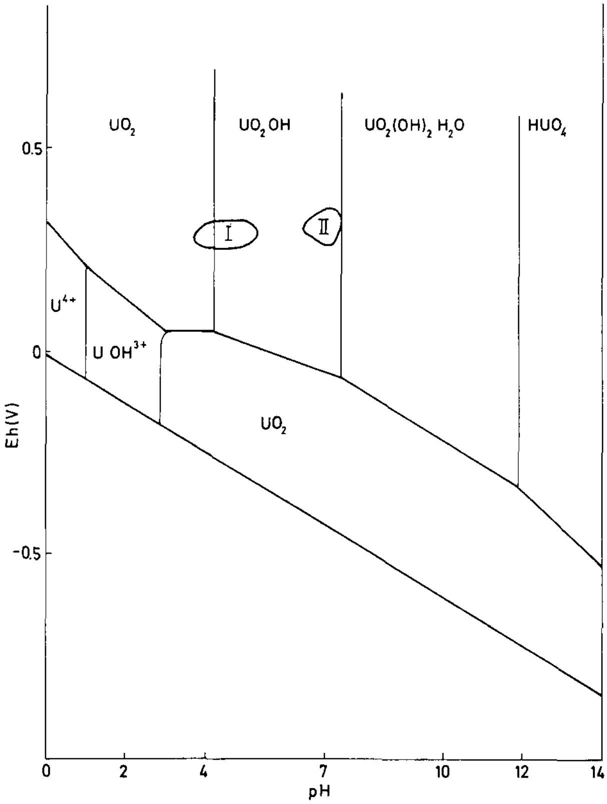

FIG.3. Aqueous equilibrium diagram of the U-O_2-H_2O system at 25°C and 1 atm. Total activity of U-bearing ions is 10^{-6}. (I) represents Eh/pH field occupied by groundwater springs in the Helmsdale granite of N. Scotland. (II) represents the field occupied by surface streams in the same granite.

The knowledge of the relationships between uranium and carbonate discussed above indicates that the interpretation of hydrogeochemical data may be facilitated by a consideration of the geology of an area, if this is known.

4.2. Sulphate and chloride complexes

Both the uranyl sulphate and chloride complexes are stable only under acid conditions of pH 3.5 or less (probably considerably less in the case of the chloride complex [9, 10]). Waters of such acidity are rare but not unknown, as oxidizing sulphides may provide the necessary sulphate and acidity to enable uranium to be readily transported. Some springs in the mining region of S.W. England carry uranium by virtue of this process and, on entering streams of different chemistry, the increase in pH and Eh results in precipitation of the uncomplexed uranium on iron oxide gels. Such scavenging is often complete and its effect is the enhancement of stream sediment anomalies of doubtful significance.

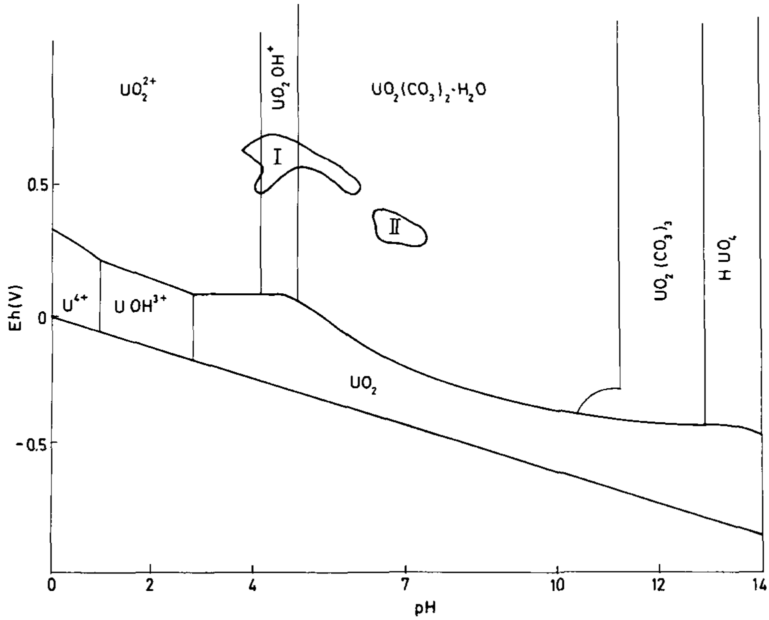

FIG.4. Aqueous equilibrium diagram of the U-O_2-H_2O-CO_2 system (25°C, 1 atm, Σ CO_2 = 10^{-3}). (I) represents field occoupied by brown earth soils in Caithness, N. Scotland. (II) represents field occupied by surface streams in Caithness. The concentration of CO_2 in the system closely approximates the composition of surface stream waters in Caithness.

5. REMOVAL OF URANIUM FROM SOLUTION

5.1. Organic matter

It has been shown that, in some conditions of water chemistry, uranium forms complexes with high dissociation constants which complicate the interpretation of hydrogeochemical data. In circumstances in which these complexes are not formed, or when changes occur in the chemical regime, the uranium in solution is available for sorption on organic material or clays, or for scavenging by, or co-precipitation with, sesquioxide gels.

A considerable amount of experimental work on the sorption effects of organic matter has been carried out [11,12]. Szalay [11] showed that the insoluble humic acid component of peat was capable of concentrating uranium from water by a factor of 10 000. Titayeva [12] showed that the degree of absorption was dependent on the chemistry of the water, so that if the uranium is complexed it is difficult to remove from solution, even by sorption on humic acid.

The importance of the carbonate complexes in influencing the sorption effects of peat is illustrated by an occurrence in the English Midlands where groundwater emerges from marl into a peat bog. The water is alkaline and contains about 200 mg $CaCO_3$/l. The stability fields of the uranium species

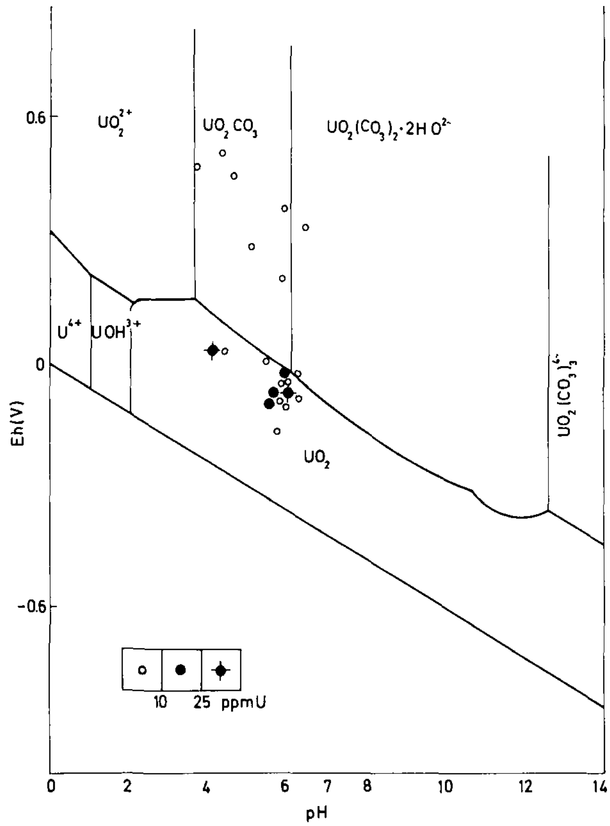

FIG. 5. Aqueous equilibrium diagram of the system U-O_2-H_2O-CO_2 (25°C, 1 atm, Σ CO_2 = 10^{-3} and total ionic activity 10^{-4}). Superimposed are Eh/pH and uranium values from a peat bog. For full explanation see text.

at this alkalinity are plotted in Fig. 5, which also includes the pH and Eh and uranium values of peat samples. It is apparent that the uranium is concentrated only in those parts of the peat bog where the carbonate complexes become unstable as a result of the reducing environment.

Meyer [13], working in Labrador, records the transport of uranium on humic acid colloids suspended in flowing water and themselves derived from the erosion of uraniferous peat bogs.

The role of organic matter in fixing and providing the means of transporting uranium must, therefore, be considered in the interpretation of geochemical survey data.

5.2. Sesquioxide precipitates

The co-precipitation of a number of metals, including uranium, with sesquioxides has also become recognized in recent years as a source of spurious anomalies not related directly to metalliferous deposits. This

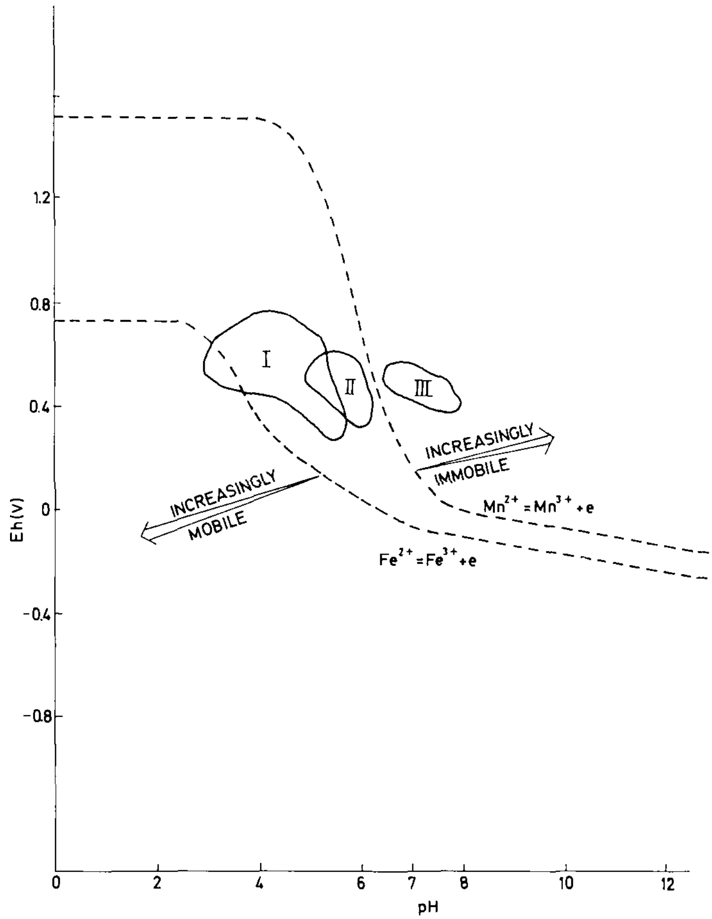

FIG.6. Approximate oxidation reaction potential for the reaction ferrous ⇌ ferric and manganous-manganic in solution. Eh/pH fields occupied by (I) peats and groundwater springs, (II) brown earth and (III) surface streams in granite areas.

interpretation problem is particularly important in acid upland environments where several tens of percent of iron and manganese oxides may be precipitated in the beds of stream courses. The reason for this is illustrated in Fig. 6, which shows the approximate oxidation reaction potentials for the reactions manganous-manganic and ferrous-ferric. Also in the diagram are the Eh/pH fields occupied by soils, groundwater and surface water from some typical granitic areas in the United Kingdom. The relative mobility for iron and manganese in soil water is high, but upon entering the environment of the stream course, precipitation occurs as a result of increased Eh.

Even small amounts of uncomplexed uranium in water will therefore tend to precipitate on these highly charged, large surface area flocs. Figure 7 compares manganese oxide and uranium in stream sediment from

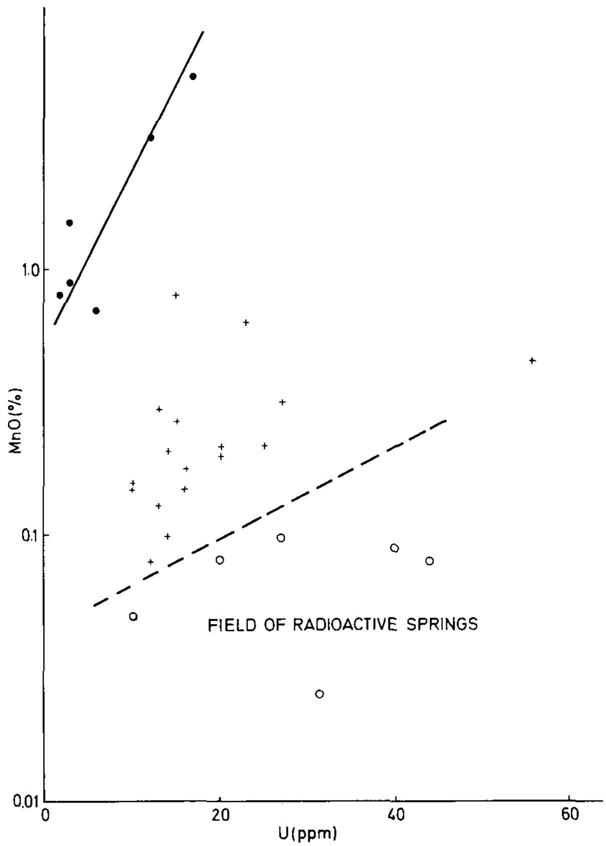

FIG.7. MnO and U from stream sediments from radioactive springs (o) and from the river into which the springs drain (+) in Dartmoor, S.W. England. Also included is a similar comparison for a part of the Gruididh granite from N. Scotland (o). ------ separates the fields of the radioactive springs and river waters in S.W. England. ——— is the least squares best fit for the N.W. Scotland data.

different environments within the Dartmoor granite of S.W. England and in samples from another granite, and shows the very marked correlation between MnO and U. It is apparent from these examples that if conditions were not suitable for the precipitation of manganese, little of the uranium in the stream water would become incorporated in the stream sediment.

5.3. Phosphate precipitates

Another condition in which anomalously high uranium concentration may occur without any relationship to the presence of discrete uranium minerals is in soils overlying calcareous structures in a dominantly acid lithology. This phenomenon is due to the formation of calcium phosphates in the soils

derived from the carbonate and the ability of authigenic phosphate to concentrate uranium from water even when the latter contains appreciable amounts of carbonate [14].

Dall'Aglio [15] records the formation of autunite in the Calabria area of Italy, where groundwaters have a very low carbonate and sulphate content and a uranium content below 1 μg/l. However, the concentration of phosphate, calcium and uranyl ion (the latter not complexed by carbonate) and the low solubility product of autunite result in the saturation of the water with respect to autunite, which precipitates on joint surfaces.

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

Geochemical prospecting techniques are finding increasing application at both the regional and local scale for the early identification of favourable areas for follow-up investigations and for the detection of discrete uranium concentrations. Considerations of the behaviour of uranium in the weathering cycle suggest that water sampling should have greater value than stream sediment sampling at the reconnaissance stage, the shorter dispersion trains in stream sediments generally having a clearer application to more local investigations. Increasing knowledge of the effects of complexing constituents of groundwaters and surface waters, and of sorption by organic matter and chemical precipitates in stream courses and soils, is providing aids to the interpretation of geochemical data.

Modern analytical methods of combined high sensitivity, precision and throughput present a choice of system for the most effective geochemical survey of regions but there appears to be scope for the development of field methods of analysis (preferably instrumental) capable of providing virtually immediate results to the field geologist at the follow-up stage of investigations.

To date, the use of associated elements behaving in a different manner from uranium has shown only limited promise as an aid to uranium discoveries but there is considerable scope for further research on this. The partitioning of uranium and radium in the dissolution of uranium-bearing minerals, coupled with the markedly different chemistry of these elements, produces useful patterns on which localized prospecting can be based, and studies of the behaviour of other decay products, e.g. ionium (^{230}Th), may provide the means of more precise interpretation of dispersion trains.

With the increasing need to employ geochemical methods to identify the more tenuous indications of uranium deposits, and with the availability of good analytical and computer facilities, an increase in the publication of case histories can be expected, which will in turn lead to better understanding of the problems of interpretation. It is in this latter area that advances are most needed.

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DISCUSSION

H.H. ADLER: I think you said something about knowledge of geochemical environments being of assistance. I would like to place a little more emphasis on that and say that it is necessary that you know what the geological and geochemical environment is in order to make intelligent use and appraisal of uranium-in-water data.

D. OSTLE: I agree but would say that it is sometimes difficult to see just where the practical application for this basic research and the basic knowledge is going to lie. To decide just how much time and effort can be devoted to basic research is a judgement that any director of an exploration program, whose main purpose is to find uranium, has to take. Some of his colleagues are bound to turn to him and ask what practical value this is but I agree that an understanding of these matters is essential to good practical operation.

H. H. ADLER: You mentioned the anion content and this is certainly important because of the complexing possibilities for uranium and the fact that natural waters do carry carbonate, sulphate and so forth. We found, too, that pH is a very important factor in areas of low uranium background. In such ground, if the pH gets down to around five and less, you might expect the uranium content to go up. We found, for example in coal-producing districts, that the values of uranium in water, which normally runs one part per billion in barren terrain, will go up to something like six parts per billion. Where you get pyritic facies, for example in certain types of rocks, you will find that the oxidation of the pyrite will give you anomalous uranium values which you can distinguish from background. Of course, when you are in an area like the Western United States, anomalies of this kind may be undetectable. Waters with contents in excess of one part per billion are not uncommon in that region because of the abundance of tuffs which introduce a considerable amount of uranium into the groundwater. In that area we are dealing sometimes with a background of closer to ten parts per billion or even higher, and so we have to make our interpretations of anomalous values beyond that point. It is important to get background values in any region that you are working in.

H. FAUTH: I estimated the pH in about five thousand water samples but I found no correlation between the content of the uranium in the water and the pH.

H. H. ADLER: What range of pH were you working with?

H. FAUTH: About 5 to 9.

H. H. ADLER: That was perhaps on the threshold. We were looking predominantly at coal-drainage waters and some of these pHs went to 2, 2.5, 3, 4 and maybe as high as 5. As you get up into higher pH ranges you appear to lose that solubilization property that is associated with pyrite oxidation.

H. FAUTH: When you want to prospect very large districts, I do not think it is necessary to estimate the pH.

H. H. ADLER: Well, I would qualify that. For example, in the Eastern United States in the states of Pennsylvania, West Virginia, Kentucky, Tennesee, Ohio, which is a very large area, the amount of coal deposits that exist is tremendous and the amount of acid waters that are released in these districts is considerable. If one were to undertake prospection there using uranium in waters as a method, and it was seriously considered because uranium occurrences are known there, one would have to be cognizant of the fact that one is in a prolific coal environment, that the dissolving power of these acid waters is considerable, and that the uranium values of the waters may very well go up. If you are in a granite terrain or something more inert you are probably not concerned with that factor.

H. FAUTH: But in this case I think you do not have the correlation of pH with uranium but the correlation of pH with pyrite.

H. H. ADLER: But coals are uraniferous and may run 10, 20, or 30 ppm U. We cannot, for example, use airborne methods in the Eastern United States without the recognition that we are likely to detect more coal deposits than uranium deposits. Our first experience with low-level flying in the eastern United States in a highly vegetated area showed anomalies which, when ground-checked, turned out to be old coal dumps that had been overgrown by vegetation and were not visible from the air. There is, therefore, a considerable amount of uranium available that is leachable by acid waters

and this gets into the streams and gives you anomalies. But these anomalies are not indicative of the type of concentrations that make for economic uranium deposits.

M. DALL'AGLIO: We determined all the major constituents and the pH on about ten thousand samples in Italy. We carefully studied the simple and multiple correlation between all these parameters and we found no significant correlation between uranium and pH value. On the contrary, we found good correlation between uranium and all the other major constituents, that is to say, the dissolution of uranium and other constituents proceed together. Also in the case of the correlation between pH and uranium, apart from the case of acid waters coming from sulphide deposits where the pH is significant, the higher pressure of carbon dioxide enables the water to be more reactive with respect to uranium and to form very soluble complexes.

H. H. ADLER: That would of course not account for the uranium in acid waters since there is no bicarbonate content when you get down to pH 4, and so it cannot be a factor. But you are obviously dealing in higher pH ranges and my comments are directed to rather unusual waters, but not uncommon conditions, and not to normal alkaline or neutral groundwaters. In sampling we have done in the Eastern United States, which is not a recognized uranium province and where we have waters with pHs of 6, 7 perhaps going to 8 and rich in bicarbonate and sulfate, we have never found more than traces of uranium (1 ppb) but when the pH goes down to about 4 or lower the uranium content goes up.

D. OSTLE: Sulphides and chlorides are stable complexes and become stable with the uranium at low pHs. The train is usually pretty short but we have not got many waters of this kind. Such as we do have arise in springs draining sulphide lodes which are high in uranium, but as soon as the waters get into the main drainage system the train disappears. So the dispersion is quite short.

J. BRINCK: May I ask a few questions about the stream sediment sampling? First, what is the average uranium value you find in the stream sediment samples? The second question is about the dispersion around the median content; does that compare also with the dispersion around the median of the rock samples? Did you ever consider using the raw data on dispersion and average content as first order criteria to estimate the potential of the area that you are investigating?

D. OSTLE: Yes certainly; we have not done this as a discrete exercise but I think we do consider this as an indication of favourability. These dispersion trains are quite short in stream sediments as far as we have been able to determine, since we are talking in terms of less than a mile in many cases. As for the values, these are comparable with the average values for the rock but they are made up of a combination of contributions from the country rock and from any concentrations within it.

J. BRINCK: We have made some attempts to use such stream sediment data for several elements other than uranium, and for these it seems to work very well to predict a kind of mineral potential for an area at an early stage of the investigation.

D. OSTLE: The problem we are up against here, of course, is the lack of information on what, in fact, the values are in the rocks, but we are getting through this problem now because we have built up a better analytical facility within the United Kingdom.

A. Y. SMITH: Most countries are making attempts to assess their mineral resource potential. The UNDP is carrying out mineral resources programs in a number of countries. Geochemical sampling, mainly stream sediment sampling, has become one of the most important techniques used in these surveys. In fact, a very large number of samples are being collected each year, representing large areas of the earth's surface. May I suggest that these facts offer us a clear opportunity to assist individual national interests and serve the wider need. I recommend that the Agency be commissioned to do the following things:

(a) Advise its Member States, and other UN agencies, to add uranium analysis to their other analytical methods and do uranium analyses on all their mineral resources survey samples, past, present and future.

(b) Advise Member States on geochemical analytical methods for uranium in soils, sediments, rocks and waters.

(c) Provide small aid programs comprising equipment and expert services for two to three months to assist Member States to do their own uranium analyses.

(d) Establish a small uranium geochemical laboratory at the Agency Headquarters to provide free or low-cost uranium analyses to Member States which have not the facilities or resources to do their own analytical work.

(e) Encourage states which have not considered a uranium program to test their areas by sending samples to the Agency laboratory, and provide advice on the most suitable type of sampling.

(f) Offer assistance in assessing the results of this program and advise on continuing the uranium program when the results are positive.

May I suggest that such a program would have several beneficial results:

(a) National geologists who are not presently acquainted with the possible uranium potential of their countries would be stimulated to consider that potential.

(b) They would be offered the means, at very low cost, to begin making assessments of that potential.

(c) The valuable geological information to be gained from uranium analysis would assist the improvement of local geological maps.

(d) A large amount of data would rapidly accumulate, allowing us to increase our knowledge of:

  (1) New areas of important uranium potential
  (2) The geochemical behavior of uranium in a wide variety of natural environments
  (3) The relationships between uranium and other ore-forming elements in the crust and in deposits.

Finally, may I quote an example of such a program. In the Geological Survey of Canada in 1967, we were faced with the problem of making some assessment of the uranium potential of the Carboniferous red-bed areas of the Maritime Provinces. In our sample storage, we had stream sediment samples of much of the area, which had been collected ten years earlier. These samples were taken out and re-analysed for uranium. The cost of the program was small but it led to the recognition of potentially favourable areas and stratigraphic units. It provided us with new information on the levels of background and anomaly in the area, and at least the first of the reports led to the staking of over a thousand mining claims. This last returned to the governments concerned revenues much greater than the cost of the program.

I believe this type of practical program will lead us to a clearer understanding of what to do next, where our future resources might lie, and which further techniques should be used or developed. May I also direct these remarks to the directors of bilateral aid programs.

GEOCHEMICAL EXPLORATION FOR URANIUM

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Abstract

GEOCHEMICAL EXPLORATION FOR URANIUM.

Geochemical methods can be of great help in all the working stages of mineral exploration. In the last decade, in fact, geochemical prospecting has also been widely applied to uranium ore exploration. The results obtained have not always fulfilled the expectations, although a complete assessment is not easy to make. This is due to various causes, organizational as well as technical, but the experience gained, though negative in part, has to be put to use in rationally planning future research.

Geochemical methods can play an indispensable role especially in the exploration surveys carried out in countries little studied from a geological and minerogenetic viewpoint, as, for instance, in the developing countries. In particular, in planning the application of the various geochemical techniques of exploration, one must keep in mind the following characteristics of this method: (a) Polymetallic surveys are the most logical and convenient type of application of geochemical exploration, (b) each of the various geochemical techniques must be employed using a sampling grid density proportioned to the dimensions of the various types of the dispersion haloes. In particular, the best application of geochemical exploration is in large-scale surveys; (c) geochemical prospecting is an essentially direct exploration technique. The data one gets from the geochemical surveys can provide the most logical link between ore genesis and exploration.

In this paper the above topics are discussed in detail. Particular emphasis is given to the planning and interpretation stages of surveys, and to the use of automatic data processing. In addition, some case histories of polymetallic geochemical surveys are given.

1. INTRODUCTION

Geochemical exploration is the application of geochemistry to the search for mineral deposits. Although it is designed for practical application, one must not forget, or for that matter even underemphasize, its connection with basic geochemical principles. Geochemistry deals primarily with:

(a) Determining both the absolute as well as the relative abundance of elements (with particular reference to the earth)
(b) Studying the distribution and migration of elements in various parts of the earth, to find the principles which govern them.

On the one hand, the continuous, intense circulation of the elements on the earth is responsible for the accumulation of elements into ore deposits. The forming of mineral deposits can be accounted for by favourable particular conditions, and especially by situations where a multi-stage accumulation process may occur.

On the other hand, however, these same geochemical processes which govern the circulation of elements bring about the dispersion of the elements, already concentrated in ore deposits. The accumulation and dispersion processes are really two sides of the same coin. In these two

opposing processes the disintegration, transportation, and deposition stages of the elements can be traced back to a few essential characteristics of the elements, and to a limited number of geochemical processes. Also, the dispersion of the elements of an ore body is at times nothing more than a process on the way to forming a new deposit [1].

Geochemical prospecting, in the narrow sense, has to do mainly with detecting secondary dispersion haloes, which are formed around mineral deposits during the disintegration of the elements concentrated there. In the zones under investigation it is possible that deposits in the stage of supergene dispersion are present. In this case geochemical prospecting can easily detect the secondary dispersion haloes. But it is just as likely that minerogenetic processes are occuring.

Even though detecting active minerogenetic processes is not as easy as detecting secondary haloes, geochemistry applied to mineral exploration definitely has to deal with this problem too, if it is agreed that the aim is:

(a) To get information as to the presence of deposits in the stage of formation
(b) To improve the knowledge of basic minerogenetic processes, which in turn will also lead to a general improvement in mineral prospecting criteria and, therefore, in the overall efficiency.

K.B. Krauskopf (1970), in his stimulating paper "The source of ore metals", maintains that: "Places where ore deposits are demonstrably forming today are very few". In our opinion this lack of data exists also because studies have seldom been made on this subject. This comes, too, from an inadequate setting up of the geochemical surveys carried out up to now. It is just as if one were to conclude that elephants are very rare animals simply because one hardly looked for them or did so in the wrong way. In our experience limited to Italy, the presence of minerogenetic processes now taking place have come to light in more than one area [2].

Geochemical exploration is the only direct approach to the problem of mineral exploration because its subject matter is precisely the distribution and circulation of the elements searched for. This method of mineral exploration permits the most direct link of ore genesis studies with exploration [1], on the condition that one plans the surveys in such a way as to collect sufficient data for understanding the geochemical processes which take place in the area under study.

In this respect geochemical exploration clearly differs from geophysical methods, which are always indirect methods in as much as they are based on the secondary or induced properties of the elements or their minerals.

This is especially pertinent in the case of uranium, where, besides geochemical prospecting methods, there are also extremely reliable geophysical ones.

A correct planning of mineral prospecting cannot be made without weighing carefully the advantages and disadvantages of the two methods, considering the aim to be met, the environmental conditions, etc. This will be gone into in greater detail in Section 2.

In the last decade, geochemical prospecting has been widely applied to the exploration for uranium. But the results have not always fulfilled expectations, although an overall assessment of the results, as far as costs are concerned, is as yet hard to make. This is due to various

factors, both technical as well as organizational. In our opinion it is mainly due to the use of geochemical prospecting as merely an applied technique, which has not kept in close enough touch with the criteria and principles of geochemistry. This has led to a large number of analyses of little use in understanding the way elements circulate in the area under study. To put this another way, the remarks made by H. V. Warren in 1965 are still to the point [3]: "Unfortunately geochemistry is suffering from occasional application under the hands of less-than-skilled operators. As a consequence of this some results are understandably less useful than they should be".

As a matter of fact, geochemical methods can be of great help in all the working stages of mineral exploration. In particular they can play an indispensable role, especially in the exploration of areas as yet little studied from the geological and minerogenetic aspects, as is the case, for example, in most of the developing countries. The planning of the surveys and the choice of techniques, however, has to be made keeping in mind the following considerations.

(a) It is, above all, indispensable to weigh critically the advantages and disadvantages of geochemical methods for the aims and scope of the exploration, and for the environmental conditions. These must then be compared with the results obtainable by other geological and geophysical exploration techniques.
(b) The most logical and convenient type of geochemical exploration is the polymetallic one.
(c) Each of the various geochemical techniques must be applied using a sampling grid density proportioned to the dimensions of the dispersion haloes involved. In particular, geochemical exploration is best applied to large-scale surveys.
(d) The data gathered this way also permits direct study of minerogenetic processes along with dispersion ones, if the information obtained is complete enough.

2. PLANNING GEOCHEMICAL SURVEYS

It is not easy to generalize the layout of geochemical surveys, since the efficiency of one's work depends on many varying factors, such as the geochemical characteristics of the elements to be found, the purpose of the search, the organizational, logistic, and economic means available, and the environmental conditions. In addition, one must continually bear in mind the possibilities offered by other methods of exploration. In spite of this, however, it still remains true that planning takes into account and includes all the other stages of surveying, and thus predetermines, in part irreversibly, the outcome of the study.

It might help at least to outline the most important steps, with the aim of correctly planning the work to be done, even if such an examination is necessarily a summary.

This paper cannot devote much discussion to the geochemical characteristics of uranium, the knowledge of which is of great importance in choosing the methods to be applied, and in interpreting the data. For more detail on this subject see, for example, Dall'Aglio [4].

2.1. Geochemical exploration and geology

Mineral exploration is closely tied in with geology. Strikingly good results can be obtained from geochemical prospecting, even without taking into account the geological conditions. This is possible because geochemical prospecting is a direct exploration technique which can, in part, leave aside model hypotheses. However, the results one gets using this prospecting method are of much greater value if they are combined with an adequate familiarity with the geological situations.

Everyone agrees on the principle that any improvements in one's knowledge of geology and geochemistry must go hand in hand, if one wants to get good overall quality results at a low cost, that is to say if one's purpose is to reach overall high efficiency. This result can be reached only if the geologist works in close collaboration with the geochemist at all the stages of exploration, from planning to the final interpretation stage. Considering the high degree of specialization in modern science, it is, in fact, almost impossible to find a skilled geologist who also knows geochemical criteria, methods and techniques well. It is equally unlikely to find a geochemist who has a good familiarity with the geology of the region studied. Experience proves, however, that this necessary collaboration seldom occurs. In fact, it is far likelier to find competition than collaboration. The failure of many geochemical prospecting surveys is, in our opinion, due to a lack of teamwork between these two specialists.

The more detailed the surveys are carried out, the more important becomes familiarity with geology, so much so that geology eventually becomes more important than the exploration technique adopted. Very detailed research is the job of the geologist who has at his disposal prospecting techniques, such as radiometry, which are equally or even more efficient than the geochemical ones.

In this case, geochemical techniques — although not the underlying geochemical principles — may play a minor role compared with the various radiometric techniques.

Geochemistry is on the other hand more useful in studying particular problems, such as, for example,

(a) Detecting the negative anomalies indicating that formation of ore bodies is going on
(b) Study of primary haloes
(c) Study of the causes and the conditions for the precipitation of secondary minerals.

Geochemical prospecting is best applied to surveys on a large or average scale, that is from 10 to 1 km on the hydrographical grid. For the purpose of preliminary reconnaissance survey, geochemical prospecting is the fastest and cheapest method, as long as the environmental conditions are favourable to its application.

2.2. Geochemical and radiometric techniques

It cannot be insisted upon enough that geochemical methods are distinctly different from geophysical ones. These differences require an accurate planning of each of the techniques and a clear-cut division of

purpose to avoid their being used when they are not best suited. In the case of uranium, radiometry works by detecting a radioactive daughter of uranium, (RaC), and this method is thus indirect. But the cost of each radiometric measurement is lower than it is for geochemical detection. Radiometric surveys can, furthermore, be easily carried out on the spot and along boreholes with the advantage of getting the measurement results right away. Every time radiometry can be used without too high a probability of making systematic errors, it is, of course, preferable to use it. It is particularly to be preferred in very detailed studies, where large quantities of radiometric measurements can be easily checked by means of a few quantitative analyses on the state of radioactive equilibrium in the rocks examined.

Geochemical prospecting is indispensable whenever there are wide zones to explore, and as long as one takes advantage of all the intrinsic possibilities of the method. It is a direct technique providing also

(a) Information on the circulation of the elements studied
(b) Indications as to the presence of minerogenetic processes now occurring.

2.3. Geochemical exploration versus total exploration

In the case of uranium prospecting, another important factor should be mentioned which has worked, and still is working, against application of geochemical methods. Generally speaking, the geochemical prospecting surveys are carried out only for uranium. This is nonsense, both from a logical as well as an organizational point of view. From the logical viewpoint, because a polymetallic exploration would be the most natural application of geochemical principles. That is to say, the increased value of the information obtained is more than proportional to the number of the elements studied. One can first of all obtain better knowledge as to distribution of the individual elements (and here the value of the information is proportional to the number of elements). But one can also get valuable knowledge as to the paragenesis and associations between the elements — and this is extra information over and above the proportional increase.

If one also looks at the organizational side, there is an advantage because most of the cost of geochemical surveys goes into field operations while the analysis and interpretation stages make up only a fractional part of the cost. In carrying out polymetallic surveys the cost of the sampling is shared between many elements, and this gives us a considerable saving for each of the elements searched for.

It must be pointed out here that the tendency to apply geochemistry in such a limited way is in contrast with what happens, for example, in the case of airborne gamma-ray spectrometry. "The gamma-ray spectrometer, the geophysical tool most commonly employed, uses screens to measure portions of the spectrum characteristic of potassium, uranium and thorium activity ... In some airborne systems the Th:U ratio can be plotted directly on the chart simultaneously with the individual readings ... As a general exploration policy for all metals, a magnetometer and electromagnetic equipment are commonly carried in the aircraft to give additional geological knowledge with some possible economic significance. The amount of information gathered in these surveys, for some areas, is

greater than can possibly be assimilated on a single exploration program, and the charts represent valuable information for future retrieval" [5].

It is, to say the least, strange that geochemical surveys are often carried out exclusively for uranium, in open contradiction with what sound geochemical principles dictate.

In airborne survey, detection is carried out for five or six parameters. In the case of geochemistry, surveys can be made for some 50 elements and for detecting a large number of natural processes (such as hot spring systems, the search for geothermal fields, etc.). One comes across this abnormal setup even in the planning of geochemical surveys carried out for international organizations such as the United Nations and the IAEA.

One more observation closely tied in with the preceding discussion is the convenience of planning the geochemical prospecting surveys in such a way as to obtain the most complete information possible on the geochemical processes taking place in the region under study. A better understanding of the geochemical processes governing the circulation of the elements in the studied region enable one to make more reliable operating decisions and thus to increase the efficiency of geochemical exploration. For this reason, in the course of hydrogeochemical surveys, it helps to collect some additional information such as the content of all the major constituents dissolved, and in the course of stream sediment exploration it helps to gather data on the distribution of the compounds causing anomalies not related to mineral deposits, such as, for example, the content of organic matter. This additional information enables one to adopt more objective and complete criteria in selecting the anomalous samples.

2.4. Pathfinder elements as a tool for geochemical exploration for uranium

It helps to employ elements different from the ones sought for especially when

(a) These elements form more widespread and/or more stable aureoles
(b) The analysis of the elements is easier
(c) The distribution of these elements provides specific enough data as to the presence of definite geochemical processes
(d) The geochemical characteristics are different from those of the element searched for, and the data obtainable are complementary and/or different from those available from the study of the element searched for. One has to know very well, however, the way the indicator elements circulate in the overall context of the region studied. In the case of geochemical exploration for uranium, the indicator elements (Se, P, Mo, V, etc.) in general do not have geochemical characteristics much more positive than those of uranium as regards their geochemical mobility or their detection.

A separate discussion needs to be given to the gaseous aureoles of some uranium daughters, such as Rn and radiogenic helium. The minerals containing uranium give off these gases even under reducing conditions and gases are, as everyone knows, very mobile and can reach the surface very quickly even starting from hidden deposits. Radon detection cannot however be thought of as a universal shortcut to the direct solution of the

problem. Very often the radon aureoles one can detect on the surface depend more on the geological feature (such as, the presence of faults) than on the presence of uranium ore bodies. Our direct experience in this regard has made clear the extreme trouble one has in interpreting the data dealing with radon distribution, in the soil gases as well as in natural waters (see below).

Last of all, one must remember that the use of indicator elements leaves out one of the essential advantages of geochemical prospecting, namely that it is a direct search technique.

The indicator elements must be used when the study of uranium distribution provides incomplete information. Generally speaking, the information obtained is of secondary importance compared with what one gets from the uranium distribution studies.

3. REGIONAL-SCALE MULTIPURPOSE GEOCHEMICAL EXPLORATION

It would help at this point to discuss briefly this type of exploration because in general it has not had much use, while in Italy it has been perfected and extensively applied. This type of exploration is actually the best approach to the exploration of little-known areas, such as in many of the developing countries. In regional-scale geochemical reconnaissance, one must get the surest possible indications of the presence of mineral deposits, with the smallest possible number of samples. For this reason, it is nonsense to gather, with low sampling density, samples of natural substances which are immobile, such as, e.g., soils. In this case the probability is too high that one loses indications of the presence of mineral deposits, and this is unacceptable. There is a real interdependence between the dispersion medium mobility, the haloes extension, the sampling density and, finally, the details of the indications one gets. In the case of preliminary geochemical reconnaissance, interest is focused on the study of hydrogeochemical and stream sediment aureoles, since these are the most widespread and stable ones. Along streams there is, in fact, a very high flux of materials coming from rock erosion. Hydrogeochemical aureoles play a complementary role compared with stream sediment aureoles. The comparative study of both these types enables one to include in such a survey a large number of elements with wide-ranging geochemical mobility. At the same time, one can apply this method under various climatic conditions. The most mobile trace elements (U, F, Zn, B, etc.) can be searched for in the stream waters, and the less mobile ones in the stream sediments. One can also study the interaction between stream waters and stream sediments.

This type of exploration is based on the analysis of water and alluvia samples, collected with regular grid, on the surface drainage system at densities ranging from 10 to 5 samples per 100 km^2. Each survey covers large areas, that is 5000 - 20 000 km^2.

The heterogeneousness of the geological, climate and hydrogeochemical conditions is very marked, also within a single survey, causing wide variations in the content of the elements, even in the absence of ore deposits. Normal and anomalous samples cannot be selected solely on the basis of the frequency distribution of the concentrations, for in this case the samples corresponding to the formations with higher background contents, or the samples of maturer waters, can appear anomalous.

To obtain an accurate geochemical classification of each water sample, it was deemed appropriate to analyse the samples for all major constituents and for some trace elements. The different geological conditions, as well as the degree and type of weathering, are recorded with the concentrations of the elements that are analysed in the stream water samples.

Study of the contents of the major constituents dissolved in the stream water samples is used to select the anomalous samples through automatic data processing (cf. Section 4). Moreover, information on the composition of the waters is also a multipurpose tool for better knowledge of the environmental conditions and of the geochemical processes which take place in the region studied. This information is not unlike the information contained in the geological map. This type of information can be of great use in the developing countries.

As an example of how information from a geochemical reconnaissance survey is a multipurpose tool, one might cite the use of the data gathered in the Tuscany Region in the course of a geochemical survey for uranium. In 1962, in the whole area of this region (approx. 20 000 km^2), a geochemical survey for uranium was made, based on the analysis of about 1000 samples of waters and an equal number of alluvia gathered with a regular grid. The results obtained in prospecting for uranium have been discussed by Dall'Aglio and Giannotti [6]. Figure 1 is a map of the water samples selected as anomalous on the basis of the procedures which will be described in Section 4.

The alluvia samples gathered in the course of this survey were also used to study the distribution of mercury. The results of this search [7] are shown in Fig. 2. It should be noted that even though the Tuscany Region is well known from the geological and minerogenetic point of view, new anomalous areas for mercury, not previously known, were spotted during this search. In the vicinity of these anomalies ore bodies were then discovered which may be of economic interest.

A list of all the analytical data related to the major and minor constituents dissolved in the surface waters was published. These data are very important for making better direct use of the waters as well as for obtaining information on pollution [8].

The data on the composition of the waters were eventually used to test a new method of geochemical prospecting for sulphide deposits. This method is based on the study of the simple and multiple correlations between the content of sulphate and the other major constituenets. It was proven that one can detect the areas where hydrothermal processes and sulphide deposits occur. Figure 3 gives the map of the sulphate anomalies discovered [9].

The results of these different types of geochemical studies carried out in Tuscany prove clearly how regional-scale geochemical reconnaissance surveys can be, and in our opinion must be, carried out. If one wants to make progress in basic geochemical knowledge as well as find a quick and cheap way of applying it, one must eliminate the present clear-cut separation between surveying for uranium and for other elements. In addition, one must break down the wall between applied and basic research.

The geochemical survey in Tuscany did not bring to light significant uranium anomalies. It was therefore decided not to continue the search for uranium in this region because the direct indications from the geochemical exploration, in agreement with our minerogenetic and geological

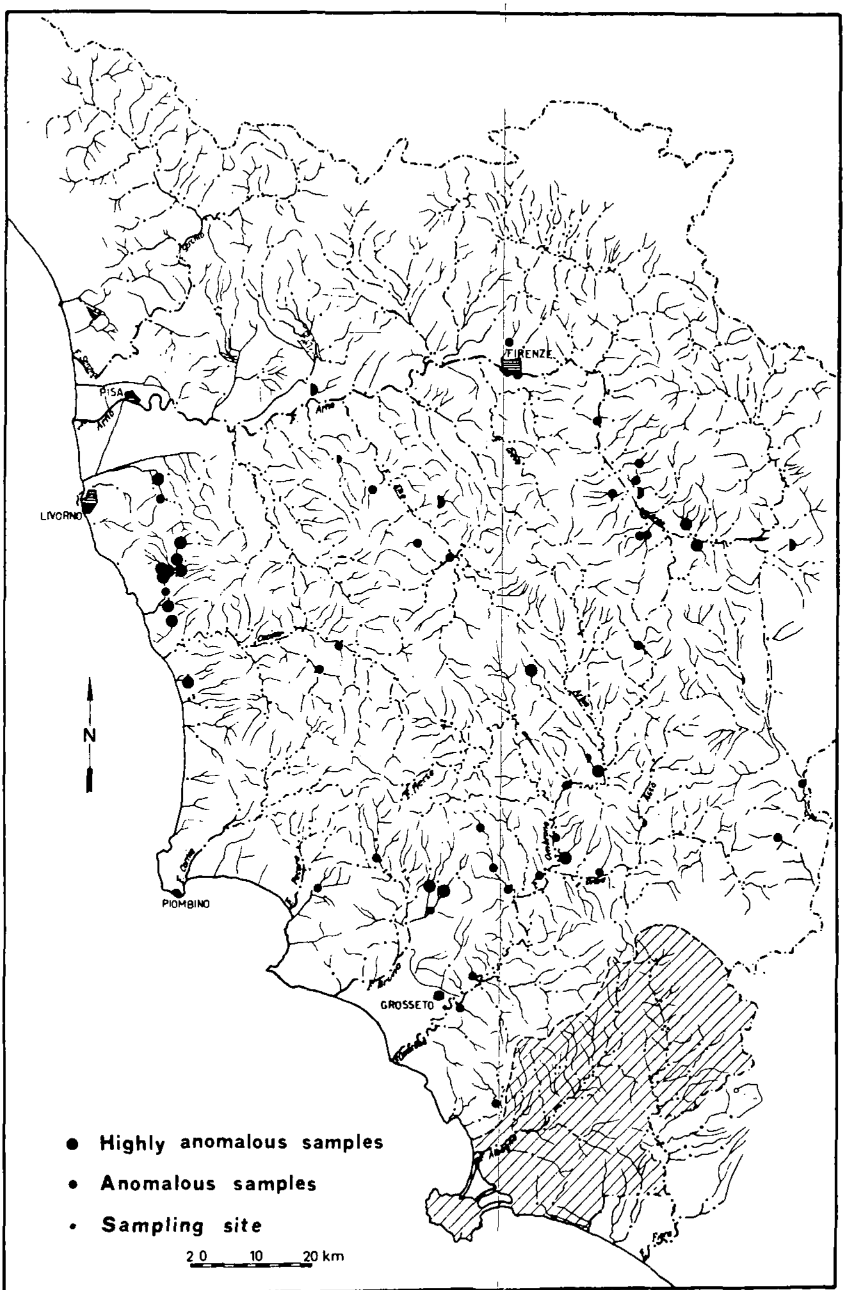

FIG. 1. Uranium anomalies found in stream water samples from Tuscany, according to the multiple regression analysis of uranium on the major constituents dissolved in waters. This procedure is discussed in Section 5.

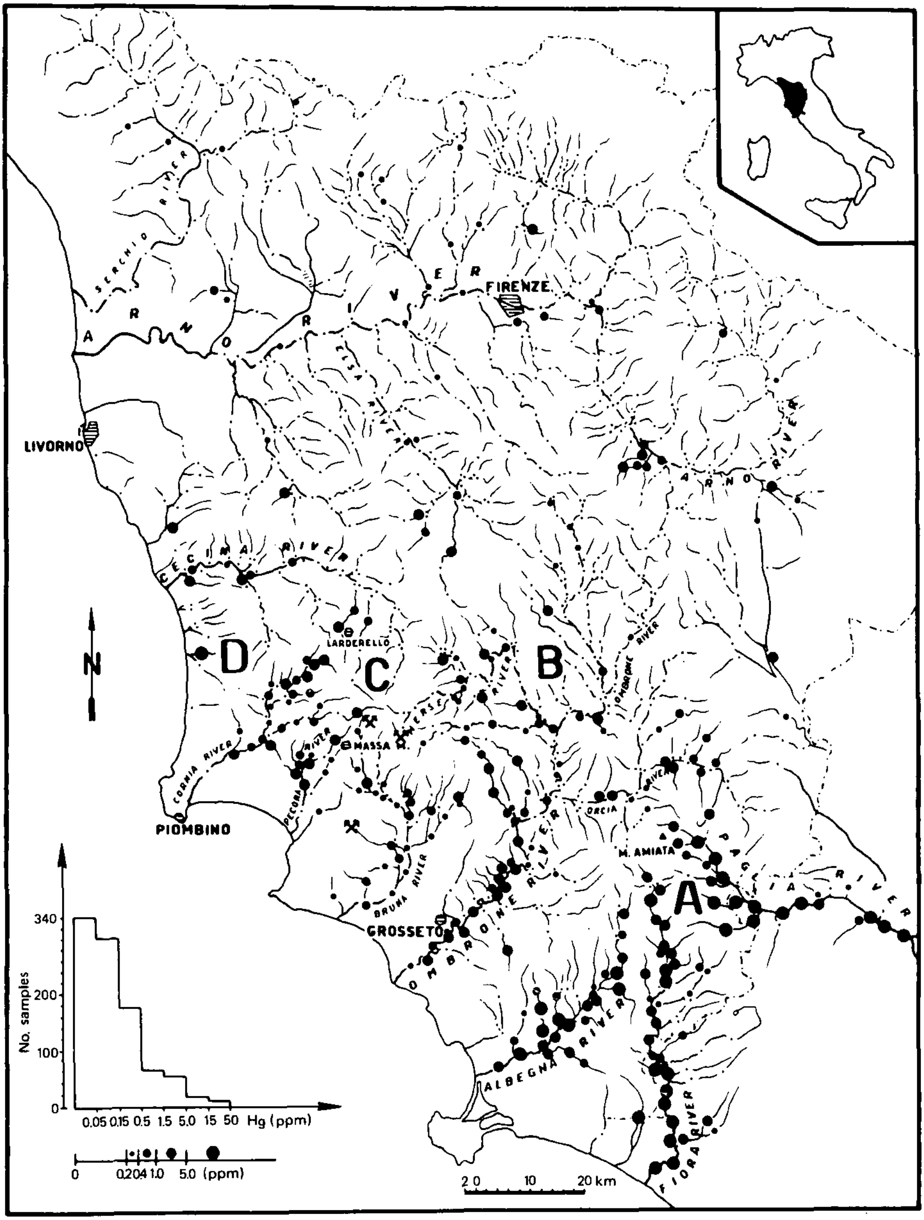

FIG. 2. Mercury haloes in stream sediment samples from Tuscany.

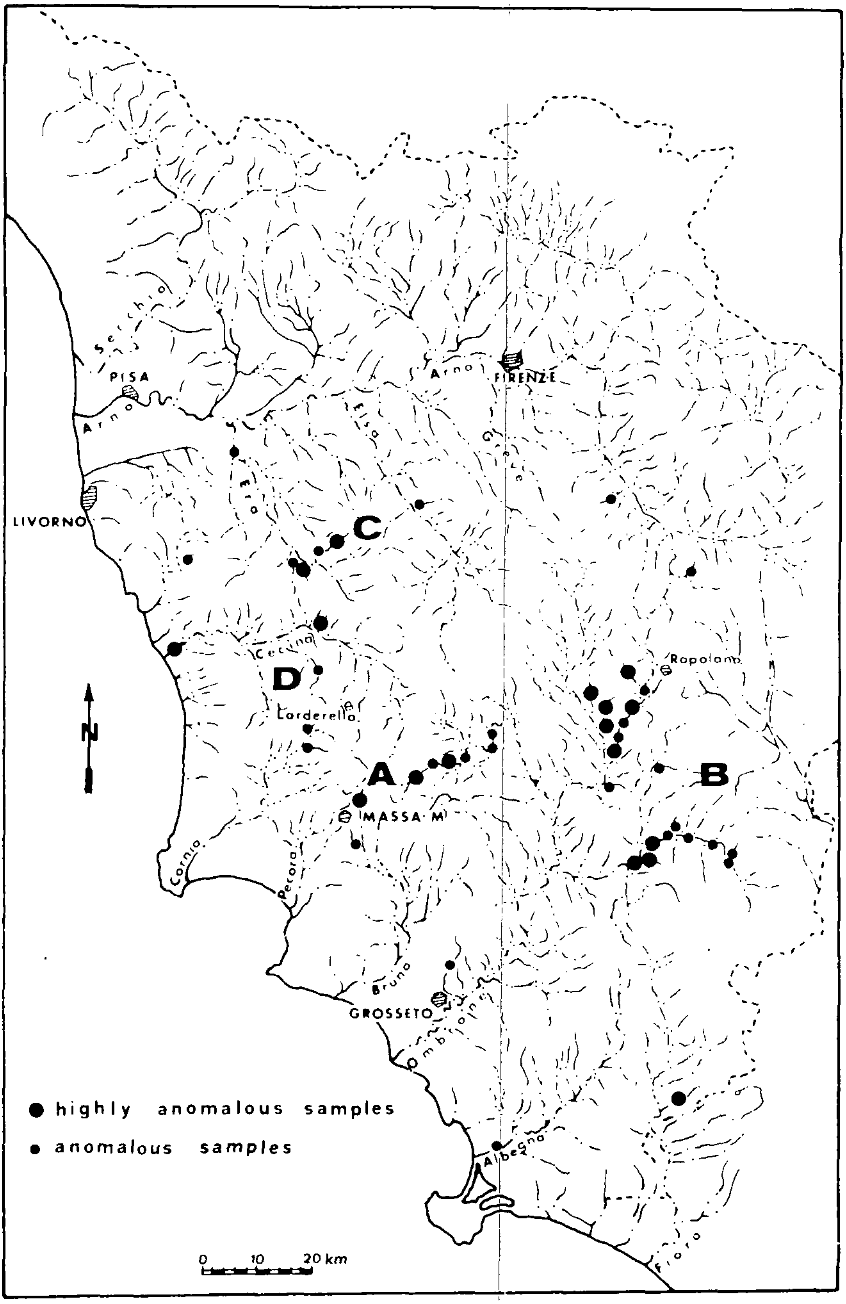

FIG. 3. Geographic distribution of stream water samples showing anomalous content of sulphate with respect to the other major constituents. These anomalous samples originate from sulphide deposits and/or systems of hydrothermal springs.

knowledge, make finding uranium deposits very improbable. In addition, our knowledge was improved of the uranium circulation in the exogenous environment, and also of the paragenesis between uranium and other elements. In fact, Tuscany is rich in many kinds of metallic deposits.

4. GEOCHEMISTRY APPLIED TO MINEROGENETIC PROCESSES

The application of geochemical principles and methods to the study of the minerogenetic processes going on can give results of great practical as well as scientific interest. A few examples illustrating this problem will be given, because in general this aspect is ignored in the treatment of the use of geochemistry in mineral exploration, even though the results obtainable in this field are just as important as those obtainable through geochemical prospecting in the narrow sense.

An example is provided by the studies which have made it possible to understand the process of autunite formation on the Sila Plateau in the Calabria Region.

Autunite mineralizations have been known for a dozen years to exist in Calabria. They have formed the object of studies and speculations concerning the hypothetical existence of a primary deposit. Hydrogeochemical studies have shown that autunite is present only in granite and where waters have a very low carbonate and sulphate content (less than 0.2 milliequivalents per litre). Taking into account the contents of phosphates, Ca and carbonates in waters, as well as the activity of the uranyl ion which is not complexed by carbonate, it appears that waters of this type are saturated with respect to autunite, even if the uranium contents are low (< 1 ppb), as are those found in the waters in question.

Table I shows the analyses of these water samples. The first represents a spring water leaching granite rock and emerging in the vicinity of autunite. The second sample is from a creek, not far from the above spring, in the basin on which there is sedimentary rock without autunite. The third water sample was extracted from diatomites bearing carnotite mineral.

The autunite is therefore formed by particular chemism of natural waters, and not by exceptionally high uranium contents. If a natural factor,

TABLE I. ANALYSES OF FRESH WATERS COLLECTED IN THE VICINITY OF AUTUNITE AND CERNOTITE MINERALS[a]

Sample	Ca	Mg	Na	K (meq/l)	Bic	SO_4	Cl	SiO_2	P_2O_5 (mmoles/l)	F	U (ppb)
1	0.18	0.06	0.37	0.027	0.29	0.07	0.28	0.36	0.002	0.007	0.64
2	1.78	0.31	0.42	0.029	2.25	0.06	0.23	0.28	0.0006	0.028	58.98
3	1.75	0.62	1.50	0.46	0.30	2.57	1.00				1.50

[a] List of samples given in text.

that is, the low concentration of chelating compounds of uranium, accounts for the precipitation of autunite, it is not necessary — and may be erroneous — to hypothesize the presence of a primary deposit which supplied large quantities of uranium.

In the vicinity of uranium occurrences in the Quaternary volcanites of the Northern Lazio [10] a study has been undertaken on the minerogenetic processes now occurring [11]. In particular, systematic drillings were made in the Legarelle basin. The waters were gathered from these bore-holes and then analysed. The Legarelle basin is a volcanic sedimentary basin on the border of a volcanic group. In this basin there are various superimposed aquifers which mix in the bore-hole. Figure 4 gives the geochemical data for the waters gathered in two series of bore-holes. The lower part of this figure refers to a zone of the basin in which one finds gases released (mainly CO_2 and H_2S) along faults. The quantity of these gases is not enough to be clearly detected at the surface. Along with the release of gases, one notices variations in the bicarbonate content, and secondarily, in the pH value. Under high CO_2 partial pressures the pH value tends in fact to diminish, and the bicarbonate content to increase. There is also a significant variation in the Eh value and in the Fe content.

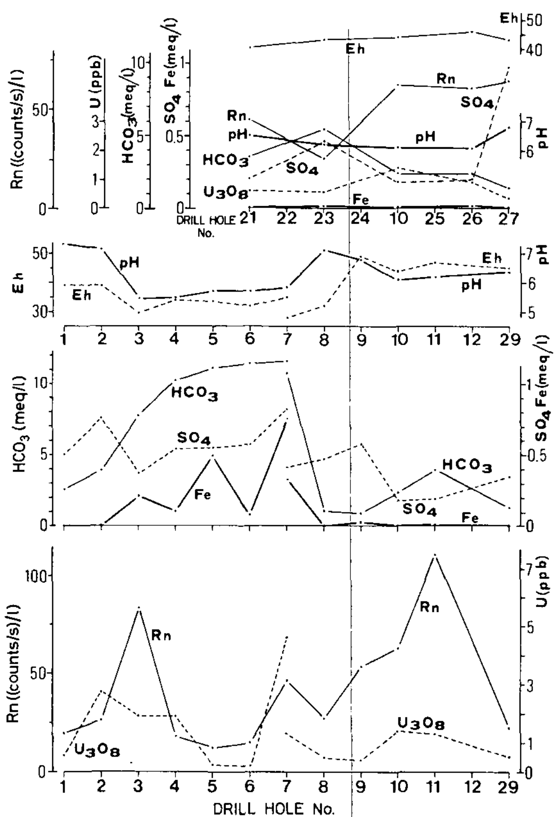

FIG. 4. Geochemistry of groundwaters collected from bore-holes drilled in the Legarelle Basin (Northern Latium).

Uranium mineralization is quite constant throughout the area explored. Nonetheless the uranium contents found in the waters vary from 0.4 to over 4 ppb, without giving a clear correlation with any other parameters determined. The radon content is clearly related neither to uranium content nor to faults.

Variations occur in the waters from bore-hole No. 7 in a few months. The variations in the Eh value and in the Fe and uranium contents should be noticed. It should also be pointed out that during the first sampling there was no odor of H_2S, while in the second this odor was clearly noticeable: the gaseous H_2S aureoles obviously spent a long time in reaching the upper part of the water table, after the drilling of the bore-holes. Even the very limited variations in the Eh value are enough to lower the uranium content by as much as two thirds.

In conclusion, the data shown help one to understand how even limited variations in the physico-chemical characteristics of the waters examined can be responsible for important uranium dissolution, transportation, and redeposition processes. Therefore, enormous variations in the physico-chemical conditions are not needed to justify the disintegration of the mineral bodies and the possible construction of new ones. From the data given, it becomes very clear how difficult the interpretation of the radon distribution in the waters can be.

5. INTERPRETATION CRITERIA IN GEOCHEMICAL EXPLORATION. THE ROLE OF AUTOMATIC DATA PROCESSING

In geochemical prospecting, the sole study of the frequency distributions of the element sought does not represent efficient criteria for the selection of anomalous samples. According to the etymological meaning, the term "anomalous" indicates a content which significantly differs from the norm. But the frequency distributions we find for the elements dissolved in waters or contained in stream sediments are of a polymodal type, and we do not have available valid criteria for assigning the examined sample to one or the other of the statistical populations which make up, with varying degrees of importance and with the relative combinations and interactions, the observed frequency distributions. And a sample may be normal or anomalous according to the statistical population to which it belongs.

The difficulty arises from: (a) the composite character of natural substances – they are always made up of mixtures which have undergone natural processes of different kinds and intensity – and (b) the existence of natural processes which can cause a high rise in the content of the searched-for element, even in the absence of mineral deposits. Among others, these processes include the amply varying background content of different geological formations, as well as differences in the environmental conditions. For example, water collected at high altitude can have a content of the element searched for quite different from the same water when it comes to a plain, because of the different degrees of the rock-water interaction, and thus of the varying degree of saturation which the waters reach with regard to the minerals. Stream sediments have a content of the element prospected for which is quite different, according to the content of precipitating compounds such as, e.g., organic matter.

For purposes of selecting anomalous samples of natural waters, according to criteria that are objective and inclusive of the variety of geochemical phenomena, an important role is played by the study of the simple and multiple correlations between the element searched for and the other elements in solution.

As outlined above, to make a proper classification of each water sample we followed the procedure of analysing all the major constituents dissolved in the waters, namely: Ca, Mg, Na, K, HCO_3^-, SO_4^{2-}, Cl^-, SiO_2.

The processes to which a water sample was subjected, including various lithological, environmental, and hydrodynamic conditions, leave their traces on the concentration of each of these elements.

If one considers the major constituents dissolved in natural waters as independent parameters and the element searched for as the dependent parameter, the random variations of this element can be noticeably reduced.

An example is presented below of the processing of the data gathered in the course of a survey made in the area of the Peloritani Mountains (Eastern Sicily). 242 samples of stream water collected with a regular grid on a surface of about 3000 km^2 were examined.

Table II shows the values of the linear correlation coefficient between uranium and each of the major constituents dissolved in the waters.

On the basis of these results, which indicate a positive correlation between uranium and the other constituents, we decided to adopt a linear function in the regression analysis of the uranium on the major constituents. The type of equation and the results of the calculation are given in Table III.

TABLE II. VALUE OF CORRELATION COEFFICIENT BETWEEN URANIUM AND THE MAJOR CONSTITUENTS

	Ca	Mg	Na	K	HCO_2	SO_4	Cl
Uranium:	0.644	0.209	0.510	0.558	0.243	0.644	0.450

TABLE III. RESULTS OF THE REGRESSION ANALYSIS

$$U = A_0 + A_1[Ca] + A_2[Mg] + A_3[Na] + A_4[K] + A_3[HCO_3] + A_6[SO_4] + A_7[Cl] \quad (1)$$

$A_0 = 0.00000074$ $\quad A_4 = 0.0189 \pm 0.000027$

$A_1 = 0.0038 \pm 0.0000010$ $\quad A_5 = -0.0031 \pm 0.0000010$

$A_2 = 0.0027 \pm 0.0000010$ $\quad A_6 = -0.0018 \pm 0.00000096$

$A_4 = 0.0026 \pm 0.0000017$ $\quad A_7 = -0.0022 \pm 0.0000013$

		DEGREE OF FREEDOM
SUMS OF SQUARES DUE TO REGRESSION	$= 22.4 \times 10^{-10}$	7
SUMS OF SQUARES RESIDUAL	$= 21.2 \times 10^{-10}$	234

F RATIO $= 35.25$

LOSS IN SUMS OF SQUARES FOR DELETED VARIABLES

$A_1 = 13.4 \times 10^{-11}$; $A_2 = 66.3 \times 10^{-12}$; $A_3 = 36.1 \times 10^{-12}$;

$A_4 = 12.0 \times 10^{-11}$; $A_5 = 88.6 \times 10^{-12}$; $A_6 = 32.6 \times 10^{-12}$;

$A_7 = 35.0 \times 10^{-12}$

R SQUARES $= 0.513$ $\quad R = 0.715$

Figure 5 shows the final results in a diagram of the determined uranium values versus the values computed on the basis of Equation (1) in Table III. The same figure indicates the samples selected as anomalous, because they differ for the value of one residual standard deviation from the regression curve. The description of the strictly statistical results obtained from the calculation will not be examined here. The data given in fact speak for themselves; notice, for example, the highly significant value of the multiple correlation coefficient, i. e. 0.716, the sum of squares due to regression, etc.

In geochemical exploration based on stream sediment analysis, the study of the correlation between the element searched for and other significant parameters can help one to understand better the processes occurring in the region studied. In this way, anomalous samples can be selected according to more objective criteria. In Fig. 6, the uranium content is plotted versus the phosphate content of 254 stream sediment samples from Western Sicily. In this region the main outcropping formations are made up of carbonate rock. The content of these two elements are directly correlated.

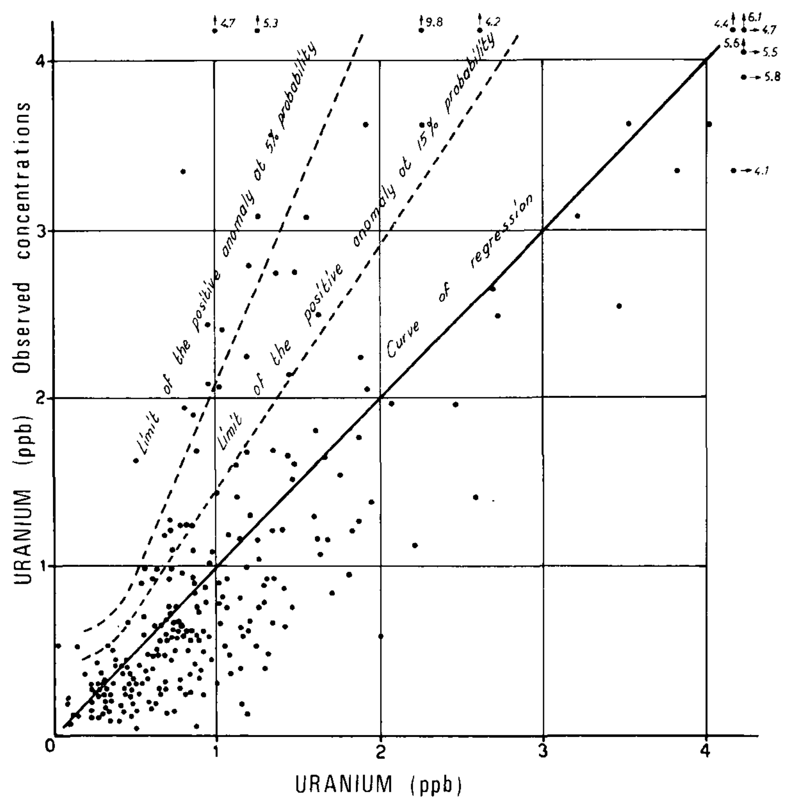

FIG. 5. Determined contents of uranium versus the contents calculated according to the multiple regression analysis:

$$U = A_0 + A_1[Ca] + A_2[Mg] + A_3[Na] + A_4[K] + A_5[HCO_3] + A_6[SO_4] + A_7[Cl]$$

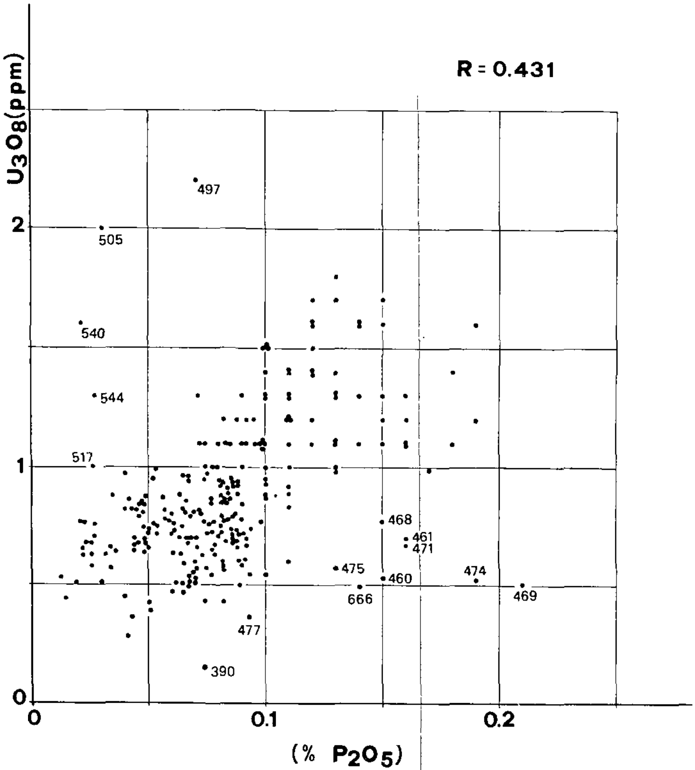

FIG. 6. Uranium content plotted versus phosphate content of 254 stream sediment samples from Western Sicily.

The anomalies we found in this area are not significant because the increase of uranium is accounted for by an increase in the content of phosphate minerals which have a high uranium content.

There are still other systems of data processing which are of great help in drawing objective and sure conclusions from the geochemical surveys, such as for example, trend analysis and factor analysis.

In our opinion, the study of the results of correlation and of regression analysis are the more effective methods for obtaining a better understanding of the geochemical processes which are at the basis of the experimental observations.

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DISCUSSION

J.F. DAVIS: This does indeed provide food for thought not only in regard to some of the points that were discussed in the paper but also, going a bit further along the same lines, in determining the favourability of large geographical areas, keeping in mind the geochemical processes responsible for ore-forming or for the ore-forming solutions. We have done some work on this with no regard to the uranium content of the water but rather to the various ratios that we might expect to be indicative of the ore-forming processes. We have done this on a rather empirical basis, making use of Geological Survey water analyses where phosphate, bicarbonate and the other salts analyses are available — I think this has got some definite possibilities in determining potential areas for exploration.

M. DALL'AGLIO: In prospecting for uranium in Quaternary volcanic environment we found negative anomalies in the springs around this plateau. Where we detected negative anomalies we had information about the possibility of mineralization that is now forming. The drilling confirmed this.

H.H. ADLER: I wonder if I can make a comment that will perhaps raise a bone of contention with the geochemists. In regard to stream sediments — you people are analysing the "daylights" out of samples and getting a minimum amount of information. I think a mineralogical approach to stream sediment analysis should be emphasized as well as the geochemical one. Stream sediments are particularly susceptible to mineralogical analysis and you do not have to be satisfied with getting simply a uranium:phosphate or a uranium:silicate correlation, which by itself does not tell you very much. In fact, you do not know what the correlation is going to be until you analyse for everything, and many, many times at that. But the mineral determination will tell you what the correlation is going to be. You can easily make a determination, for example, on whether the uranium and phosphate are in autunite or in xenotime and by this you can also appraise the economic significance of that particular sample, which you cannot do from chemical analysis alone. I want to emphasize here that I think we should be looking to mineralogical analysis

as well as, and perhaps instead of, geochemical analysis in those cases where you are dealing with solid materials.

M. DALL'AGLIO: We did study in some detail the possibilities offered by mineralogical alluvial prospecting and geochemical prospecting. In the case of uranium we did not find mineralogical prospection to be a good aid. We found that information about the gross composition of the alluvial stream minerals in relation to uranium content could be a good aid.

A. G. DARNLEY: I should just like to make a comment on Mr. Adler's remarks. I am very sympathetic to the idea of undertaking mineralogical examinations but I wonder whether this is practicable in terms of sample throughput. How do you think this would compare with automated forms of geochemical analysis in terms of the cost and time required? Would you envisage doing all samples this way or a selected proportion?

H. H ADLER: As you know, there is something on the order of a hundred or so uranium minerals, and the more resistant of these are going to be found in the stream sediment simply because they are not soluble and because they are not easily leachable, and the composition of these uranium resistate minerals varies considerably. We have had many years of experience with intensive mineralogical analysis of steam sediment. We have put through literally thousands of samples using magnetic separation, gravity separation and various other techniques and, although it takes a little bit of experience, good technicians can be trained to handle the problem extremely well, as the uraniferous or thorianiferous (radioactive) fractions of stream samples can be isolated in a relatively short time. As far as cost is concerned this has to be measured in terms of the requirement. You may not get the same volume of data, but I think you are going to get considerably more informative data initially from the mineralogical study than you will from the chemical study. The chemical analysis will give you the overall chemical composition of the sample but it will not give you any concept of the combination in which these elements occur. The mineral composition also goes a long way to establishing the economic value of what you are working with.

S. H. U. BOWIE (Chairman): In our own experience in this particular field we find now that mineralogy is not particularly fashionable. It is very difficult to find a good mineralogist these days and it is a time-consuming job unless you have somebody who is fairly experienced for this kind of work. But, in fact, once you have got some experience, it is possible to look at stream sediments in such a way as to get a lot of mineralogical data without using microscopes. What we have decided to do, because of this difficulty in getting people to do mineralogical work on our samples, is to look at them chemically. We are actually using an automatic XRF set-up to look at the samples first of all; we use this to select the samples that we subsequently study mineralogically. This seems to be working quite well. We have also tried it in the reverse process, looking at the samples mineralogically first and analysing them afterwards. This is something we have only recently started to do but it looks very promising.

H. H. ADLER: Yes, there are all sorts of shortcuts that you can take, and one we have used in mineralogical analysis is to get a representative granular fraction, sprinkle this onto a fusion of sodium fluoride-carbonate and just barely bring this to a melting point, and then apply ultraviolet light so that you can recognize the grains that are uraniferous, because

the technique is extremely sensitive — 0.01% uranium in a mineral will show up. You can then isolate these grains, and because they have not been attacked by the reagent except peripherally you can pick them off the fusion plate and then do whatever is necessary to make further identification. Then, if you wish, what you could do is get an emission spectrograph reading using very simple equipment which gives you almost the entire spectrum of elements that are associated with that grain. This is going to tell you an awful lot about that sample, whether you are dealing with a titanate or with a silicate, etc. You can develop these methods in the cheapest possible fashion. If you want to go to X-ray analysis you can identify the mineral specifically, but it often is not necessary. I still think there is a lot to be said for this approach in spite of the fact that mineralogical analysis seems to be becoming a lost art.

H. FAUTH: This has a very high interest for the scientific geologist, but I think we must also consider the practical geologist who is prospecting in the field and the company who pays for all these determinations. Geochemical determinations are very expensive in relation to the radiometric methods, and radiometric methods are unable to estimate uranium in water. It is difficult to estimate 2 ppm uranium in stream sediments, but I ask myself what is the practical purpose of 2 ppm uranium results in stream sediments; I think the minimum must be 20, 30 or 50 ppm to be of interest. When I find such low contents in the stream sediments I forget it and look at the higher contents only. Because of this I have not got much experience in the estimation of uranium in stream sediments, because I think that it is possible to find nearly the same information with a scintillation counter. The scintillation counter is cheaper and therefore I stopped this work of uranium analysis in the stream sediments and only estimate uranium in water.

M. DALL'AGLIO: I would like to mention that we made an accurate assessment of the cost of the different parts of the operating stages of geochemical exploration. The most costly stage is the sampling, which, in our experience, accounts for more than 60% of the costs. All the analytical work which is carried out in the laboratory accounts for only a small part of the total cost because it is possible to carry it out automatically. Sampling cannot be carried out automatically. When you have a sample already collected, it is erroneous in my opinion not to analyse it fully, even if the content is lower than maybe 2 ppm. If you carry out geochemical prospecting in strict collaboration with the geologists, even this information about the low content in the sediments is good information, and effective in aiding the geologist in taking operative decisions.

HYDROGEOCHEMICAL RECONNAISSANCE PROSPECTING

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Abstract

HYDROGEOCHEMICAL RECONNAISSANCE PROSPECTING.

Hydrogeochemical reconnaissance prospecting by the chemical determination of uranium in springs, streams and wells has the advantage that it can indicate uranium enrichments not only at the surface but also at depth. By modifying the procedure, this method was so improved as to be quicker and cheaper than airborne and carborne prospecting. The water samples are collected in 2-litre polyethylene bottles and are analysed in the laboratory trailer by the following method: precipitation of the uranium by ferric hydroxide; separation from the disturbing elements by tributyl-phosphate; and determination of the uranium using a cathode-ray polarograph. About 70-90 analyses can be made per man and working day. Depending on the number of samples (max. 300/d) the mobile laboratory must be operated by one to four people of whom at least one must be an assistant chemist. The laboratory costs per sample is about US $1. The costs of sampling depend mainly on conditions in the survey area, $1.0 per sample under the most favourable, $10.0 under the least. Uranium prospecting in the Black Forest (Schwarzwald), Federal Republic of Germany, is given as a detailed example. So far, about 30 000 samples, collected in the Federal Republic, Peru, Mali, Togo, Ghana, Mozambique, Angola and other countries, have been analysed by this method. The method has worked very well under the most difficult climatic and terrain conditions and has been perfected for prospecting in developing countries.

1. INTRODUCTION

Until now only a small part of uranium prospecting has been done using geochemical methods. The measurement of radioactive radiation of uranium proved to be essentially simpler and cheaper than the chemical determination of uranium.

The drawback of the radiation methods is, however, that they do not always show uranium specifically and are not always sensitive enough. This is particularly so when determining the uranium content in water.

The uranium background in water, which depends, as is well known, on the matrix, varies between 0.2 - 1 ppb uranium. Since uranium is fairly mobile, geochemically speaking, it is relatively certain that an enrichment of uranium in the soil and rocks should show up as an increase in the uranium content of the corresponding groundwater. Hence, the conditions for a geochemical reconnaissance survey are, accordingly, favourable.

2. METHOD OF ANALYSIS

Since the concentration of uranium in water is so small, it is necessary to concentrate it and separate it from disturbing elements before determining the quantity.

The concentration of the uranium from the 2-litre water sample is achieved by trace adsorption with ferric hydroxide. After the precipitate has settled, and the water has been decanted, the ferric hydroxide is dissolved in nitric acid. The uranium is then selectively separated from this solution by tributyl-phosphate and then re-extracted. Using a sulphuric-perchloric acid solution, the uranium content is determined by a cathode-ray polarograph. This method has the advantage, compared with fluorometric and colorimetric methods, that the failures caused by other elements can be distinguished. The (lower) detection limit is about 0.2 ppb uranium. The relative analytic error is between 20 - 60% depending on the working conditions.

3. THE MOBILE LABORATORY

The trace investigation of water should, whenever possible, be carried out on the same day as sampling. The trace content can quickly be altered by adsorption onto the bottle walls, and by the action of microorganisms. For this reason we use a laboratory trailer.

The mobile laboratory is a trailer of 4 tons weight and some 4 m long. It is a fully equipped laboratory. It is towed by a Unimog and can move over any terrain. It can be made economically self-sufficient in any climatic region and needs only petrol for the maintenance of its power supply. The water supply can be any river, spring or well within 300 m distance. In favourable climates the investigations can, however, also be carried out under tents.

FIG. 1. Laboratory trailer in Peru.

Depending on the number of samples (max. 300/d), the mobile laboratory needs between one and four people to operate it, of whom at least one must be an assistant chemist.

4. COSTS

An average of 70 - 90 uranium analyses can be made per man and working day. The general laboratory costs (personnel, chemicals, energy supply, and depreciation of equipment) amount to about US $1.0 per analysis.

The costs of water sampling (personnel, vehicle operation) mainly depend on the conditions in the survey area. Under ideal conditions they amount to about $1.0 per sample, and under the least favourable conditions to about $10.0 per sample.

It is estimated that a 5-man fully equipped prospecting team for sampling and analysing will cost about $300/d.

5. INVESTIGATION EXAMPLES

5.1. General

Up till now some 30 000 samples, which have been collected in countries including Angola, the Federal Republic of Germany, Ghana, Mali, Mozambique, Peru and Togo, have been treated according to this method.

Thus, this method has proved efficient under the most difficult survey area conditions and is most suitable for use in developing countries.

5.2. Detailed example

In the following section an example from uranium prospecting in the Black Forest is discussed in detail.

From a survey area of some 5000 km^2, about 5000 water samples were collected during 1962/63 and analysed for uranium in the manner described above. A mean of 150 samples were treated per working day.

6. EVALUATION OF RESULTS

From the regional maps, the coordinates of the sample points, using a digitizing table, and the field results subdivided into 10 value classes were punched onto paper tape. The diagrams given in Figs 2-4 were then drawn by a computer-controlled platter (Graphomat).

Moreover a statistical calculation from the results was made. The cumulative frequency distribution of the uranium content resulting from this is reproduced in Fig. 5. Since the (lower) detection limit of the analysis lies within the normal background, a lognormal distribution only holds for the higher values.

In addition, a trend surface analysis up to the 7th degree was calculated. But the degree of significance reached was only 12.2%. The results have not been represented here because of this relatively high inaccuracy and because a better interpretation can be made from the results shown in Figs 2-4.

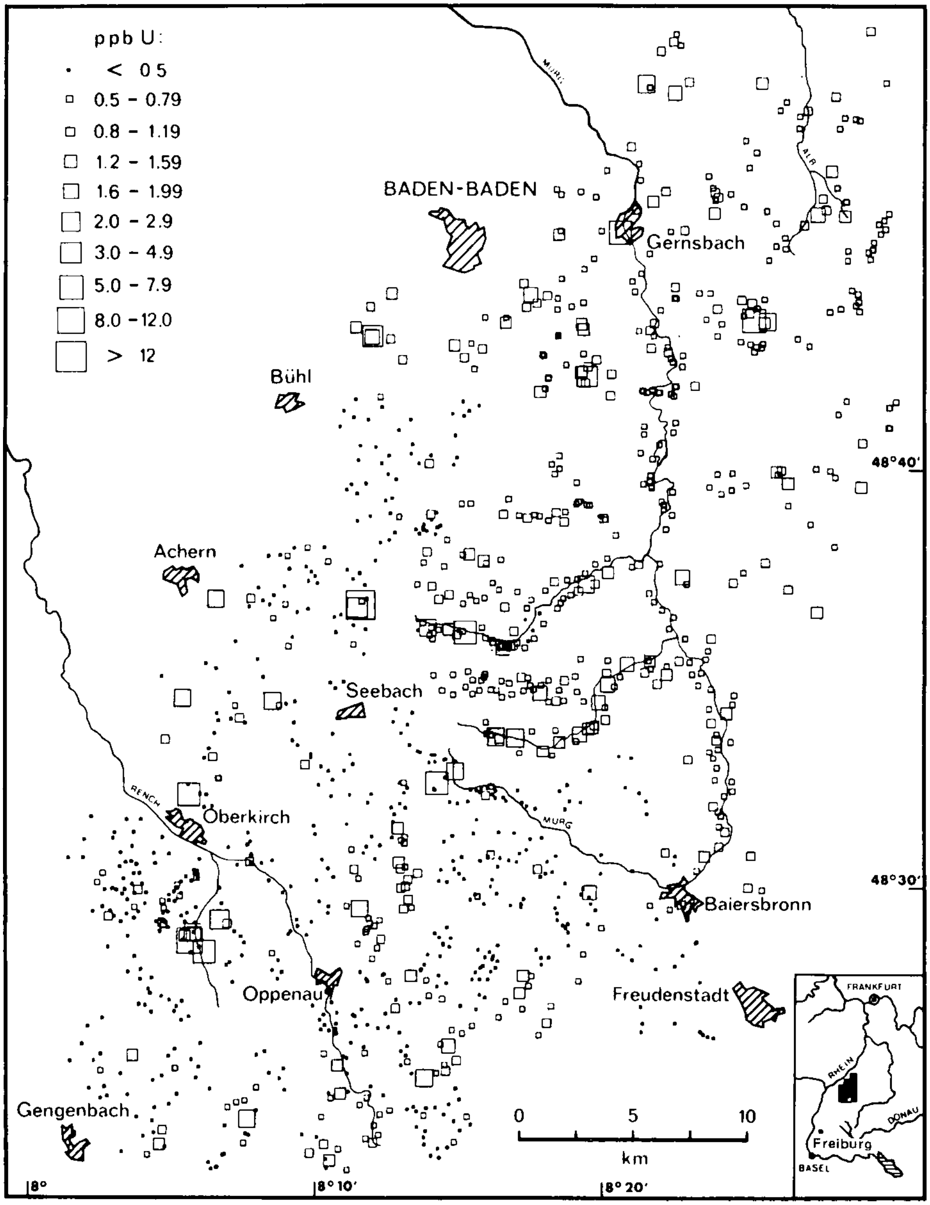

FIG. 2. Uranium content in water samples: survey area 1.

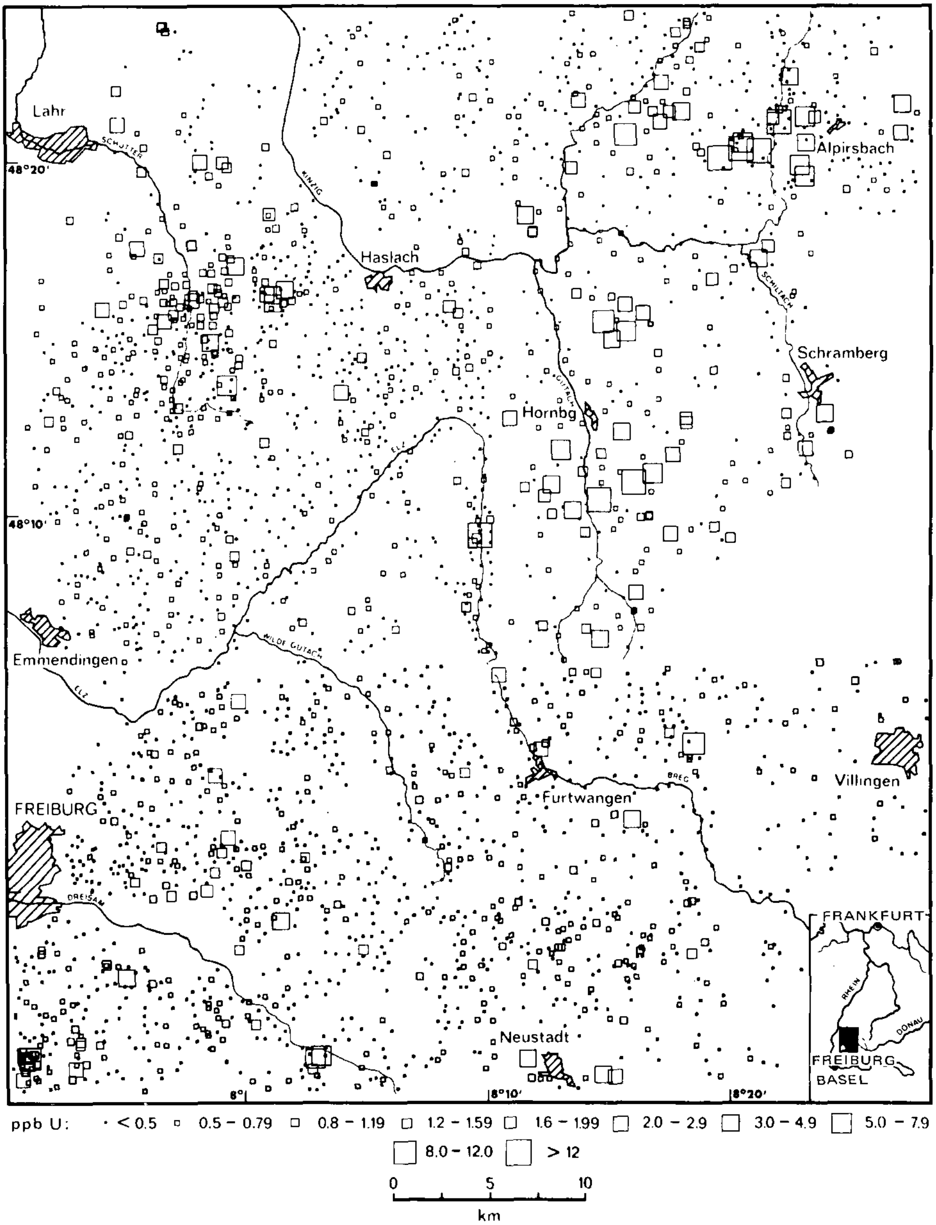

FIG. 3. Uranium content in water samples: survey area 2.

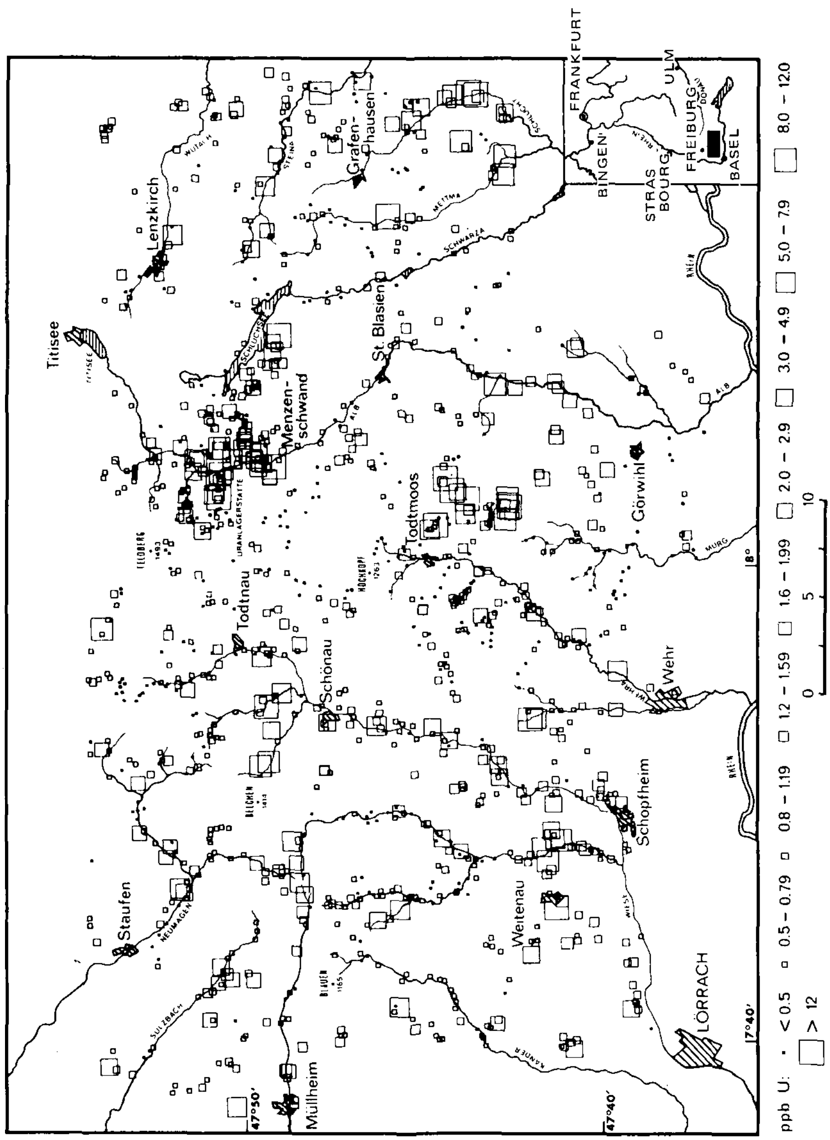

FIG. 4. Uranium content in water samples: survey area 3.

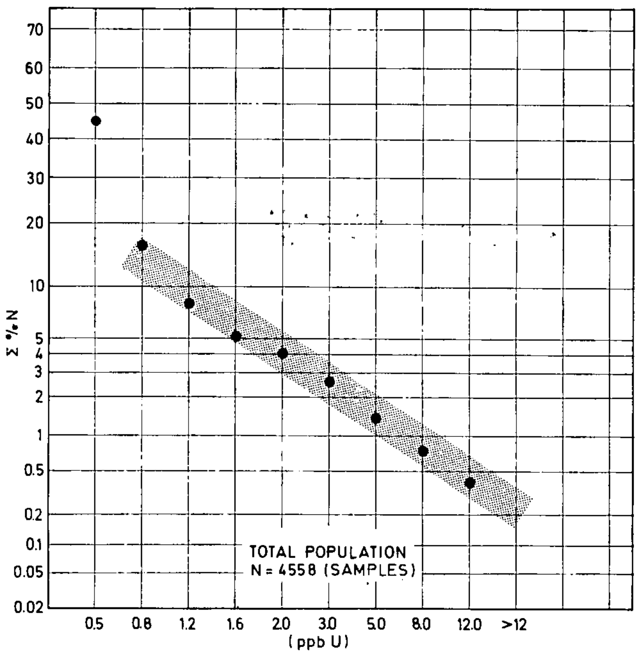

FIG. 5. Cumulative frequency distribution of uranium content.

7. SUMMARY OF RESULTS

The results of these geochemical investigations can be summarized as follows:

(a) In the survey area the background value in the water is 0.5 ppb uranium, the threshold 3.00 ppb uranium.
(b) All the known, small, uranium deposits in the Black Forest, as for example at Alpirsbach (see Fig. 3) and Menzenschwand (see Fig. 4) were positively identified by this method.
(c) Numerous indications of further uranium can be identified, but the analysis data cannot be used quantitatively to assess a deposit.

8. CONCLUSIONS

By all further analogous investigations it can be similarly established that this prospecting method is a relatively sensitive and certain way to indicate uranium enrichments. In some cases where the area had been thoroughly surveyed by radiometric methods without success, this method, however, gave positive results. This also holds true in several developing countries.

In all cases, only a qualitative, and not quantitative, evaluation of the general results is possible since, as a rule, there is no relation

between the height of the uranium water anomaly and the size or degree of enrichment of the corresponding uranium deposit.

For this reason this method is good, first of all, as a relatively certain negative indicator. This means that over a large region, using a widely spaced grid of sample points, areas are quickly demarked in which there is only a little chance of finding uranium. The areas which remain after this (those where the possibilities of uranium deposits are higher) should be investigated intensively using radiometric and geological methods.

DISCUSSION

S. H. U. BOWIE (Chairman): I would like to open this discussion myself by saying that I am very interested in the practical work you have done and in your attempt to quantify parameters not normally amenable to this kind of processing. However, I think that trying to equate parts per million uranium, either in water or in stream sediments, to the probability of finding a workable uranium deposit is something that we have got to guard against. There are so many factors that come into the problem that it is not really possible to do this. I am also very interested in the fact that you are using a mobile laboratory that is fully equipped for analytical work, and in the cathode-ray polarograph which I have not actually used for this kind of analysis. I wonder if you could say approximately what this kind of instrument costs? I notice that you say in the paper that it compares favourably with other analytical methods.

H. FAUTH: This polarograph is an English one and costs nearly $6000. You can estimate that this polarograph can deal with sixty samples in one hour if you are working hard and for normal work about half of that. In reply to your first question, we took nearly 30 000 samples in the district where several enrichments of uranium were known and we never failed to find even little deposits by these methods, but it is impossible to say that an anomaly must be an economic uranium deposit. But when you have a district where you find no anomalies in the water, you will find no anomalies by scintillation methods either.

M. DALL'AGLIO: What is the absolute sensitivity of the polarographic equipment and the quantity of the samples to be analysed?

H. FAUTH: We must take 2 litres of water and then concentrate the uranium collected on ferric hydroxide and send the concentrate of about 1 ml to the polagraphic cell where we can estimate maybe 1 ppm uranium or a little lower.

M. DALL'AGLIO: The absolute sensitivity is on the order of 1 μg.

H. FAUTH: Yes.

H. H. ADLER: I wonder if anyone here could venture to say just how many ore deposits have, to date, been discovered by this geochemical approach and what this represents in terms of tonnage. If we look at the past fifteen years or ten years of experiences of applying geochemistry, can we measure from that what the prospects are for the future?

S. H. U. BOWIE: I would say, Mr. Adler, that the past does not recapitulate the future in this case.

H. H. ADLER: That is an easy way out.

S. H. U. BOWIE: The reason for this is that we all know that geochemical methods have not been applied on the same universal scale as

have radiometric methods of all kinds, whether they be airborne, carborne or on-foot surveys. I think that it is quite true to say that the geochemical techniques are really just coming into their own, and what is making them so important, at the present time and in the future, is that they can detect, as Mr. Fauth has told us, deposits or occurrences that are not detectable by radiometric methods. We have got to use all the techniques that are available to us, and this, of course, depends on the particular environment in which we are. We all know this anyway but perhaps it ought to be recorded that this is the case. This is also one of the reasons why I do not think we can make any predictions on what we are going to find in the future by using geochemical methods, but it does look very important to me. One other thing I want to emphasize is that analytical techniques are so much better now than they were ten or fifteen years ago. In our own case where we use neutron activation analysis this has changed the whole concept of taking geochemical samples and having them analysed. It has simplified the whole thing to the extent that this now becomes a feasible proposition.

H. H. ADLER: I would like to make a recommendation to the Secretary that we should try to get a tabulation of the effectiveness of this approach within the next five years. This will indicate that, if we find nothing, we are going too slowly, or it will indicate that it may not be until the year 2020 before this becomes an effective method, or that it is just not working and is not effective in the sense that we are not finding ore deposits by this technique. If that proves to be the case we certainly do not want to put too much emphasis on it. I am trying to throw a little bit of cold water on this, not because I do not believe in geochemistry but I think we ought to play the devil's advocate here with regard to some of these methods.

J. F. DAVIS: I could also say that I do not believe that we have made one discovery through the use of one single method. In neither my company's case nor in my own personal experience can I think of one individual method which has been solely responsible for leading us into a discovery. However, I can say that water sampling or hydrogeochemical sampling for uranium has led us much more rapidly into an area. In one area we have outlined approximately ten million pounds of contained uranium oxide, and we were led much more rapidly into that area by anomalies in the range of 10-50 ppb against a background of 2 ppb.

A. G. DARNLEY: Delegates may be interested to know that the Geological Survey of Canada will be carrying out a survey over about 100 000 km^2 this coming summer, taking geochemical samples (lake water and lake sediment) on the basis of one per 25 km^2. At the same time, the area will be flown with our gamma-ray spectrometer at a 5-km line spacing. The area is in the Northwest Territories, southeast of Great Bear Lake and the northwest corner of it touches the old Port Radium uranium district. The geochemical analysis is going to be multi-element, so the comparative results should be extremely interesting.

S. H. U. BOWIE: As I do not think it has been mentioned in any of the papers, there is another thing I want to ask somebody who has done some work in this field, and that is the association of uranium with manganese in stream sediments, particularly in fine-grained material.

A. Y. SMITH: In our Canadian experience there is no relation between manganese and uranium. In the Maritime Provinces, for example, or in the Shield, we have not found any significant correlation between manganese and uranium at all. In Ireland, I believe it has been the same thing. Iron

hydroxides often concentrate uranium, but not manganese hydroxides. I think this is what Mr. Bowie was referring to. Of far greater importance, at least in cold climates, is the chelating effect of organic matter. We are finding that the uranium background in stream sediments in Greece is far lower than in Canada, while the background in water is higher. In my view this must be due to the abundance of organic matter in most Canadian stream sediments. At the Geological Survey of Canada we employed a fluorimetric technique for uranium in both water and solid samples (soils, stream sediments, and rocks). For water, 5 ml are evaporated on a platinum dish and fused with 3 g of mixed carbonate-fluoride flux. The detection limit is 0.1 μg/l (ppb) and it is easily possible to determine uranium in 200 samples/d. One advantage of this method is the small sample required, another is that no collection or concentration step is required. We would normally collect 250 ml of water because radon was being determined as well. But if only uranium were wanted, 50 ml would be more than enough. We are now employing this method in our work in Greece (UNDP/IAEA Project: Uranium Reconnaissance of Northern Greece) with excellent results. Our background levels appear to be on the order of 0.5 - 1 ppb.

I would also like to lend my support to Mr. Bowie and Mr. Davis' remarks addressed to Mr. Adler. Surely we have learned by now that there is no "best method" of exploration for uranium or anything else. Dr. Duncan Derry in Canada has attempted several times to classify successes for the various methods of exploration. His findings are, to say the least, controversial. And I know of no one who has changed his methods as a result of these findings. They have, however, provided a number of geophysical companies and contractors with good sales promotion material.

In our Greek project, we are trying to apply a selection of reconnaissance methods to lead us to areas of greatest uranium potential. These include carborne scintillometry and stream sediment and water geochemical methods. We consider that they complement each other very well. But perhaps we are not really trying, at this point, to find deposits, but to eliminate some of our 28 000 km^2.

A STUDY ON THE BEHAVIOUR OF RADON IN SOIL*

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Abstract

A STUDY ON THE BEHAVIOUR OF RADON IN SOIL.

Measurements of radon were made over widely separated areas. The fluctuations were statistically studied. Values over some areas arranged themselves in a single lognormal distribution while in some others the data resolved itself in two distinct lognormal distributions when plotted on probability paper. Geologically the areas showing a single distribution are known to be unmineralized. Those showing a double distribution are found to be mineralized and contain varying uranium enrichment though not of any economic value. As in the mining industry, an attempt has been made to see if the two types of distributions are related to the nature of mineralization. No generalization can be made at this stage, and further studies are in progress to confirm if any such correlation really exists. An experiment to test the results was made by injecting radon in one of the holes and taking measurements in the surrounding holes.

1. INTRODUCTION

The free radon content of the soil has wide variations, as is shown by day-to-day measurements carried out over long periods at the same measuring point and between one measuring point and another nearby on the same day. It is therefore not possible, from the observations made, to assign a unique radon value to an area, and one can, to be practical, talk in terms of probable values only. The data were treated by the well-known statistical method of class intervals and cumulative frequencies and plotted on probability paper. When this was done a difference in the behaviour of the data from different areas and, in some cases, from some holes in the same area was noticeable. In some areas, whether taken singly for each hole or jointly for all, the data showed a single lognormal distribution. In others, there was a deviation from lognormality in the sense that the data fitted better on two distinct lognormal distributions.

That the meteorological conditions could not have determined the difference in behaviour can be seen from the fact that the data for the same area, collected over two periods when the meteorological conditions are drastically different, did not show any difference in behaviour. One might then seek an explanation of this difference in behaviour in the known geological differences of the areas.

2. MEASUREMENTS

Radon measurements were carried out in the areas listed below. The equipment used for the measurements is simple. It consists of a ZnS (Ag)

* This work is being done under an IAEA Research Contract with S.G. Tewari and P.C. Ghosh as co-investigators.

TABLE I. FREQUENCY DISTRIBUTION OF DAILY RADON COUNTS FOR DELHI-AREA A

AREA (Delhi-A) February to June 1971

(1) Average U_3O_8 in Soil : 4.7 ppm in the range 3 to 5 ppm·
(2) Range of radon values in 9 auger holes : 0.45 to 2.1 pCi/cm^3.
(3) Calibration factor : 1000 counts/min = 6 pCi/cm^3.

Class interval	Frequency								
(counts/min)	Hole: A-1	A-2	A-3	B-1	B-2	C-1	C-2	D-1	D-2
60 - 90	0	1	1	0	0	0	5	0	0
90 - 120	8	7	16	1	7	3	8	0	7
120 - 150	16	9	13	5	10	13	3	5	27
150 - 180	5	11	8	10	8	9	10	14	7
180 - 210	5	6	5	17	10	16	7	11	4
210 - 240	8	7	4	14	8	2	9	12	0
240 - 270	2	5	0	1	2	1	3	3	0
270 - 300	2	0	0	1	0	1	0	2	1
300 - 330	0	1	0	0	0	0	0	1	0
330 - 360	1	0	0	0	0	0	0	0	0

TABLE II. FREQUENCY DISTRIBUTION OF DAILY RADON COUNTS FOR DELHI-AREA B

AREA (Delhi-B) June to September 1971

(1) Average U_3O_8 in Soil : 4.7 ppm in the range 3 to 5 ppm.
(2) Range of radon values : 0.63 to 3.87 pCi/cm^3.
(3) Calibration factor : 1000 counts/min = 6 pCi/cm^3.

Class interval	Frequency								
(counts/min)	Hole A	B	C	D	E	F	G	H	I
90 - 120	1	0	0	0	1	3	1	3	0
120 - 150	5	1	0	0	1	4	3	5	1
150 - 180	5	0	0	1	0	5	7	4	2
180 - 210	4	5	0	0	4	6	11	3	2
210 - 240	8	10	0	0	1	6	6	6	4
240 - 270	16	5	6	1	6	4	3	2	5
270 - 300	7	5	8	2	12	2	6	3	12
300 - 330	-	2	10	1	10	1	4	6	6
330 - 360	-	10	6	5	8	2	2	6	2
360 - 390	-	6	7	3	3	1	0	6	2
360 - 420	-	0	6	2	1	-	-	-	1
420 - 450	-	1	6	7	3	-	-	-	-
450 - 480	-	2	1	5	2	-	-	-	-
480 - 510	-	3	2	1	-	-	-	-	-
510 - 540	-	2	-	1	-	-	-	-	-
540 - 570	-	-	-	0	-	-	-	-	-
570 - 600	-	-	-	6	-	-	-	-	-
600 - 630	-	-	-	4	-	-	-	-	-
630 - 660	-	-	-	3	-	-	-	-	-

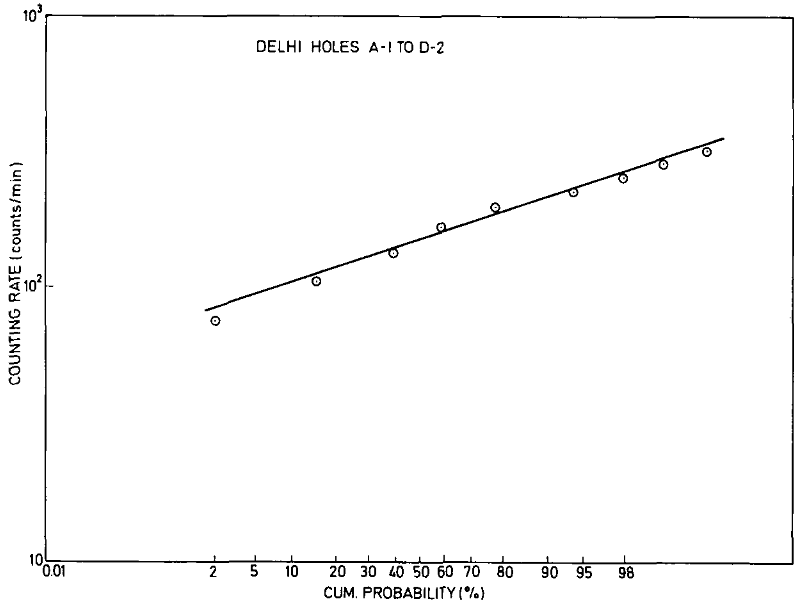

FIG. 1. Log-probability plot of radon values at Delhi (area A) showing a single lognormal distribution.

coated chamber as a detector into which the radon is collected from the bottom part of the hole after circulation with a hand rubber pump to ensure uniformity of the mixture. The chamber is then closed and taken for counting under a photomultiplier tube. Important precautions to be taken are that the phosphor at no stage should be exposed to light and that there are no leakages in the detector. If there is the slightest suspicion of this, the sample is rejected. The calibration is carried out with the help of radium chloride solution of known strength.

2.1. Delhi, Area A and B

The daily radon count was recorded in each of the 9 holes at sites A and B in the laboratory ground and grouped as in Table I and II. The data for each of the 9 holes at A and B with the exception of holes E and I fitted into a single lognormal distribution. Data for the E and I holes showed a deviation from lognormality and fitted better into two lognormal distributions. When data for the holes at site A were taken jointly, the result was still a single lognormal distribution (Fig. 1). The data for site B when taken jointly gave two lognormal distributions (Fig. 2) in spite of the fact that only E and I holes had shown two lognormal distributions (Fig. 3 and 4), thereby showing that the double distribution character dominates. Why E and I might have given a distribution different from the 16 holes in the same locality is considered later. Further, taking all the 9 holes at site A and the 7 holes at site B which had each given a single lognormal distribution, the result was again a single distribution (Fig. 5).

The observations over site A were taken from February to June 1971 and over site B from June to September 1971. It is interesting to note that

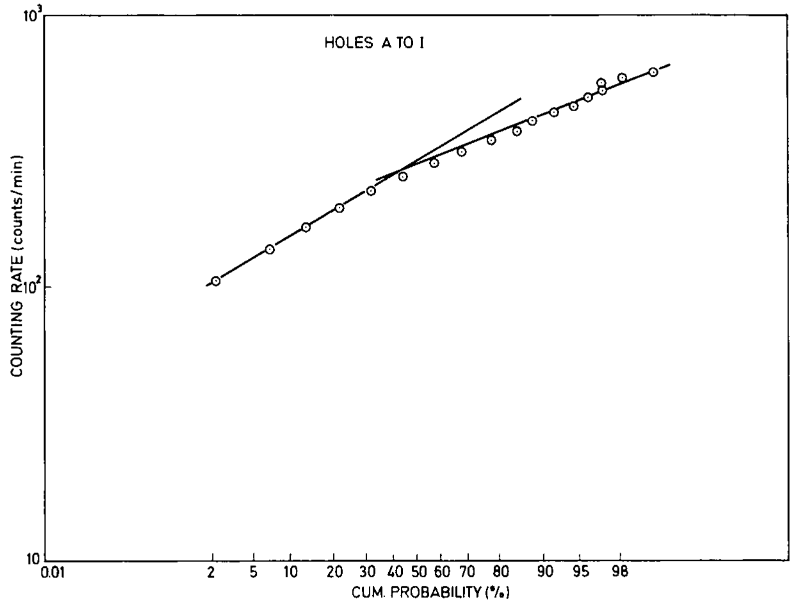

FIG. 2. Log-probability plot of radon values at Delhi (area B) showing two lognormal distributions.

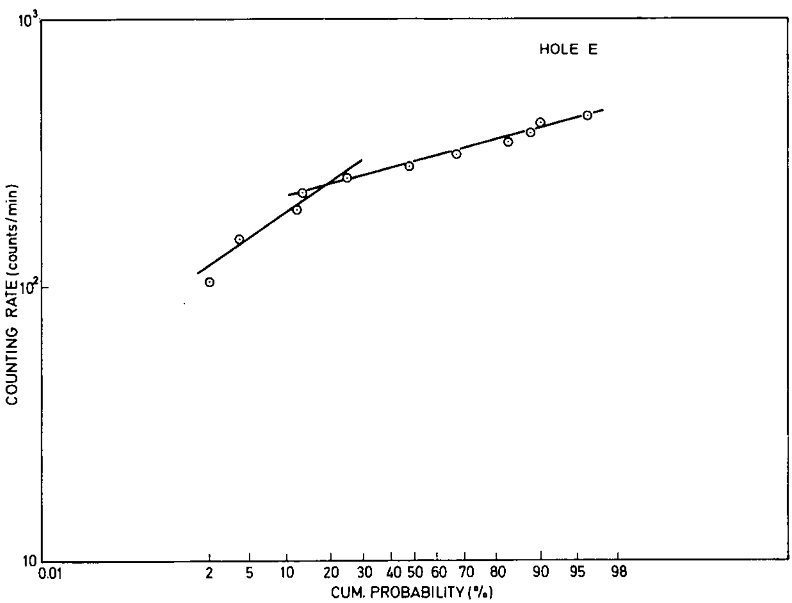

FIG. 3. Log-probability plot of radon values for hole E located at Delhi (area B) showing two lognormal distributions.

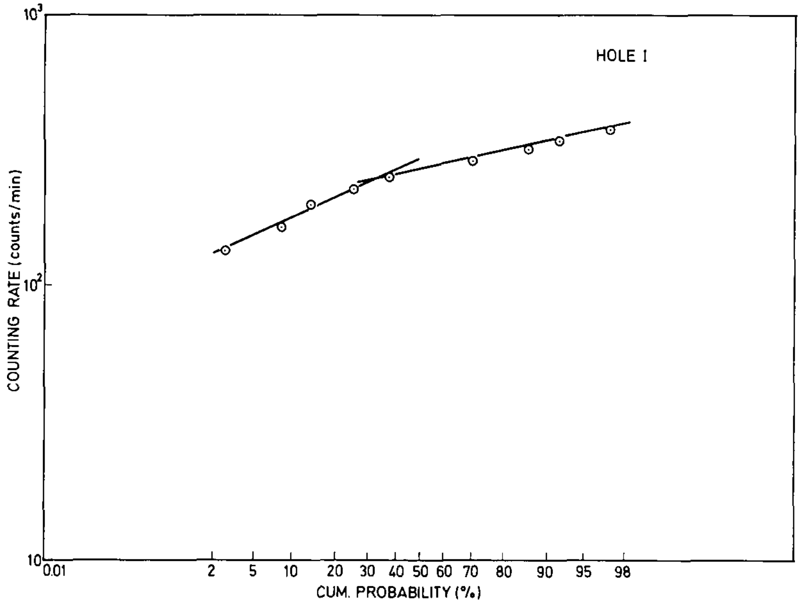

FIG.4. Log-probability plot of radon values for hole I located at Delhi (area B) showing two lognormal distributions.

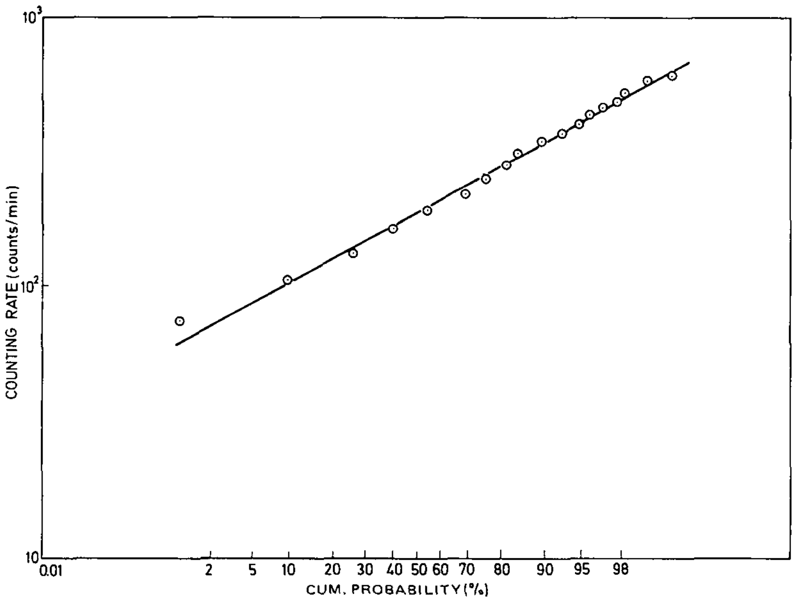

FIG.5. Log-probability plot of radon values at Delhi (areas A and B), leaving out the holes E and I at area B, shows a single lognormal distribution.

TABLE III. COMBINED FREQUENCY DISTRIBUTION OF RADON VALUES IN NINE AUGER HOLES

AREA Mehrauli February to March 1972

(1) Average U_3O_8 in Soil : 6.2 ppm in the range 2.2 to 9.1 ppm.
(2) Range of radon values : 0.39 to 3.96 pCi/cm^3.
(3) Calibration factor : 1000 counts/min = 6 pCi/cm^3.

Class Interval (counts/min)	Frequency	Cum. Frequency	% Cum. Probability
50 - 85	1	1	0.8
85 -120	7	8	6.6
120 -155	9	17	14
155 -190	17	34	28
190 -225	17	51	42
225 -260	23	74	60.7
260 -295	10	84	68.9
295 -330	6	90	73.8
330 -365	7	97	79.5
365 -400	3	100	82
400 -435	2	102	83.6
435 -470	4	106	86.9
470 -505	3	109	89.4
505 -540	4	113	92.7
540 -575	4	117	96
575 -610	3	120	98.4
610 -645	1	121	99.2
645 -680	1	122	100

in spite of large meteorological changes which took place during this long observation period of February to September and which seemed to have affected the range of values of radon content, the combined data for both sites follows a single lognormal distribution. Thus one may call this distribution a characteristic of this locality.

2.2. Mehrauli

In another area about 30 km south of Delhi, daily radon measurements were made over 9 holes. The frequency distribution is shown in Table III. The entire data of this set of holes was distributed lognormally (Fig. 6).

2.3. Rajasthan

2.3.1. Banera

Six auger holes were made in this area in the soil-covered region, and the radon data (Table IV) subjected to the lognormality test. It was found that there was a departure from lognormality. Two distinct lognormal populations of radon were obtained in this area (Fig. 7).

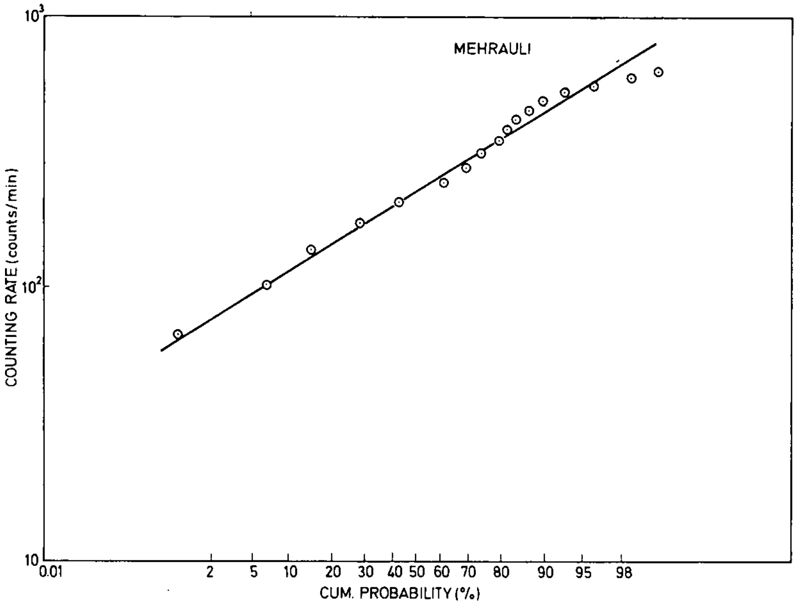

FIG. 6. Log-probability plot of radon values at Mehrauli (30 km south of Delhi) showing a single lognormal distribution.

TABLE IV. COMBINED FREQUENCY DISTRIBUTION OF RADON VALUES IN SIX AUGER HOLES

AREA Rajasthan (Banera) November 1971 to February 1972

(1) Average U_3O_8 in Soil : 3.7 ppm in the range 1.7 to 6 ppm.
(2) Range of radon values : 0.048 to 0.76 pCi/cm^3.
(3) Calibration factor : 1000 counts/min = 6 pCi/cm^3.

Class Interval (counts/min)	Frequency	Cum. Frequency	% Cum. Probability
0 - 15	12	12	8.2
15 - 30	37	49	33.3
30 - 45	34	83	56.5
45 - 60	30	113	76.9
60 - 75	24	137	93.2
75 - 90	6	143	97.3
90 -105	2	145	98.6
105 -120	1	146	99.3
120 -135	1	147	100

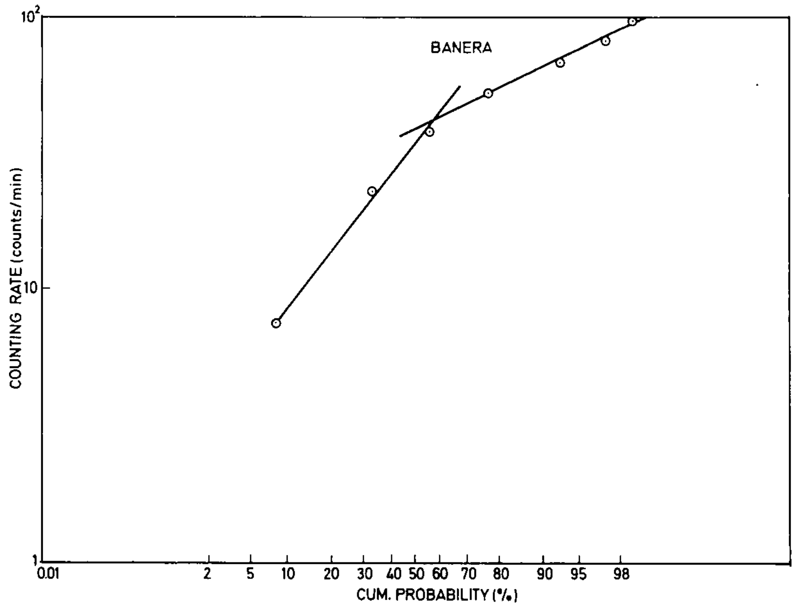

FIG. 7. Log-probability plot of radon values at Banera, Distr. Bhilwara, Rajasthan, showing two lognormal distributions.

TABLE V. COMBINED FREQUENCY DISTRIBUTION OF RADON VALUES IN TEN AUGER HOLES

AREA Rajasthan (North Dedwas) January to March 1972

(1) Average U_3O_8 in Soil : 2.5 ppm in the range 1.8 to 3.0 ppm.
(2) Range of radon values : 0.048 to 0.6 pCi/cm^3.
(3) Calibration factor : 1000 counts/min = 6 pCi/cm^3.

Class Interval (counts/min)	Frequency	Cum. Frequency	% Cum. Probability
0 - 15	22	22	22
15 - 30	32	54	54
30 - 45	19	73	73
45 - 60	18	91	91
60 - 75	7	98	98
75 - 90	0	98	98
90 -105	2	100	100

2.3.2. North Dedwas

Radon measurements were taken in 10 auger holes every day. The entire data (Table V) shows departure from lognormality and two lognormal populations of radon have been obtained in this area (Fig. 8). Truncation of the data into two groups of 5 holes each also showed the same behaviour.

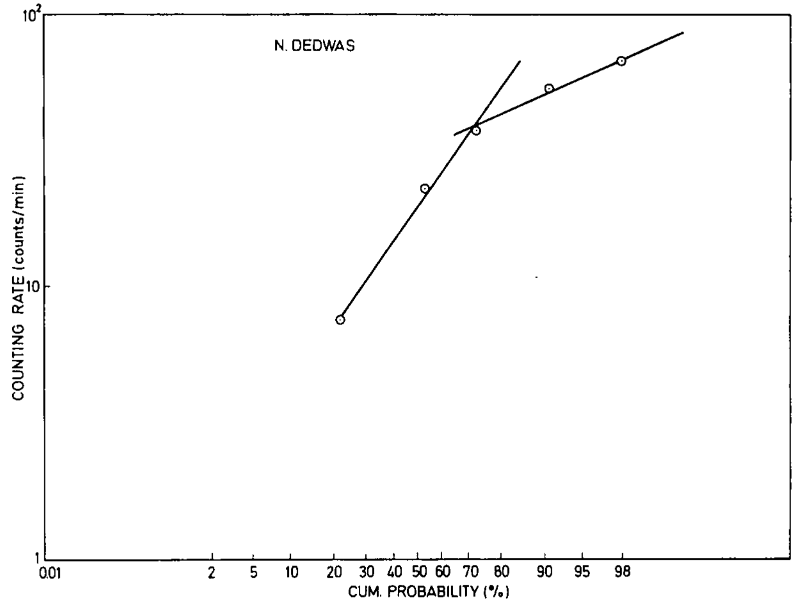

FIG. 8. Log-probability plot of radon values at North Dedwas, Distr. Bhilwara, Rajasthan, showing two lognormal distributions.

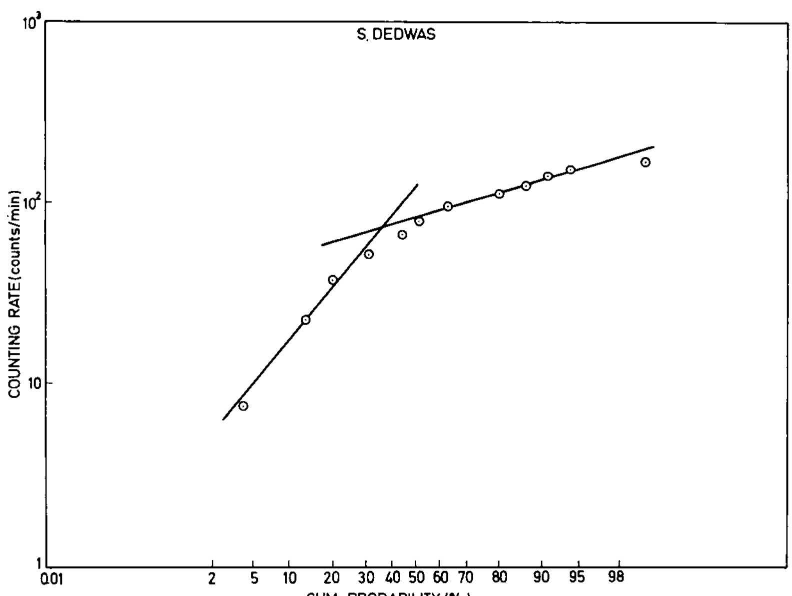

FIG. 9. Log-probability plot of radon values at South Dedwas, Distr. Bhilwara, Rajasthan, showing two lognormal distributions.

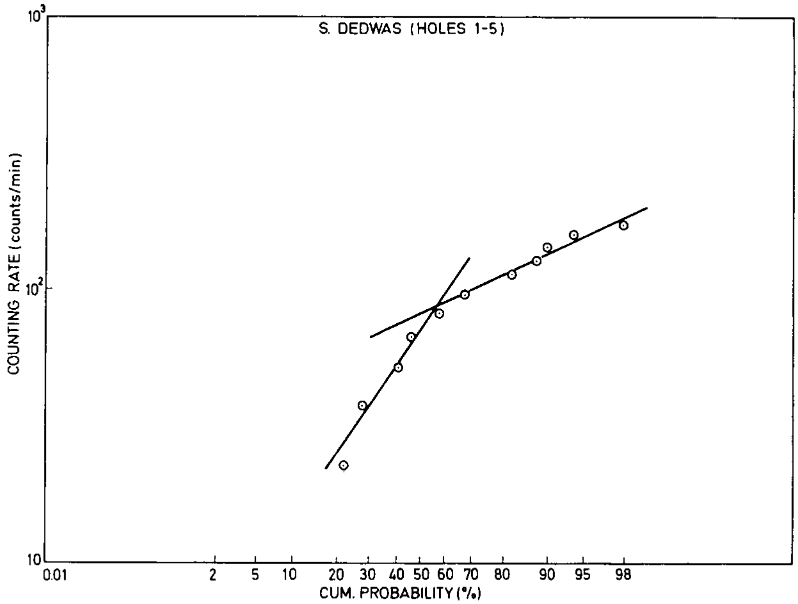

FIG. 9a. Log-probability plot of radon values at South Dedwas, for holes 1-5, showing two lognormal distributions.

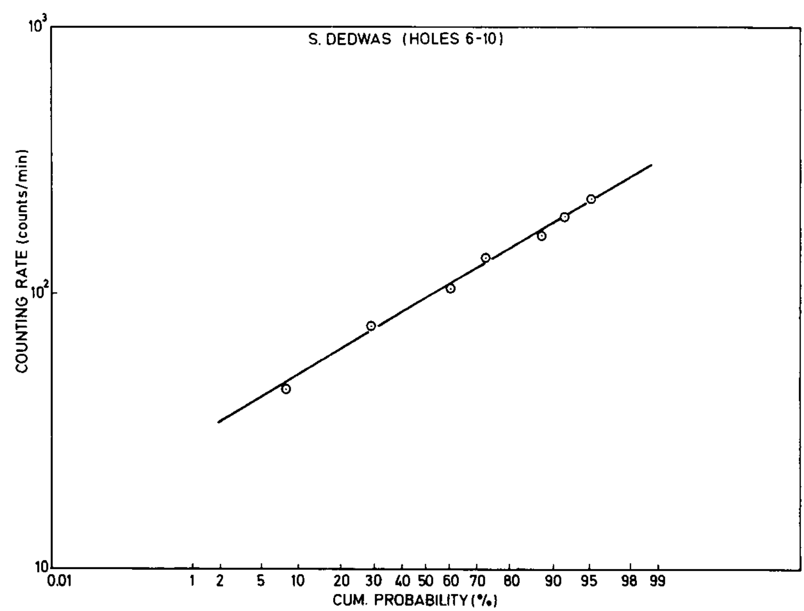

FIG. 9b. Log-probability plot of radon values at South Dedwas for holes 6-10 (downdip), showing a single lognormal distribution.

TABLE VI. COMBINED FREQUENCY DISTRIBUTION OF RADON VALUES IN TEN AUGER HOLES

AREA Rajasthan (South Dedwas) January to March 1972

(1) Average U_3O_8 in Soil : 1.9 ppm in the range 1.2 to 2.6 ppm.
(2) Range of radon values : 0.05 to 1.1 pCi/cm^3.
(3) Calibration factor : 1000 counts/min = 6 pCi/cm^3.

Class Interval (counts/min)	Frequency	Cum. Frequency	% Cum. Probability
0 - 15	4	4	4
15 - 30	9	13	13
30 - 45	7	20	20
45 - 60	11	31	31
60 - 75	13	44	44
75 - 90	7	51	51
90 -105	12	63	63
105 -120	17	80	80
120 -135	7	87	87
135 -150	4	91	91
150 -165	3	94	94
165 -180	5	99	99
180 -195	1	100	100

TABLE VIa. FREQUENCY DISTRIBUTION OF RADON VALUES IN HOLES 1-5

AREA : South Dedwas

Class Interval (counts/min)	Frequency	Cum. Frequency	% Cum. Probability
0- 15	4	4	8
15- 30	7	11	22
30- 45	3	14	28
45- 60	6	20	40
60- 75	3	23	46
75- 90	6	29	58
90-105	5	34	68
105-120	7	41	82
120-135	3	44	88
135-150	1	45	90
150-165	2	47	94
165-180	2	49	98
180-195	1	50	100

TABLE VIb. FREQUENCY DISTRIBUTION OF RADON VALUES IN HOLES 6-10

AREA : South Dedwas[a]

Class Interval (counts/min)	Frequency	Cum. Frequency	% Cum. Probability
0– 30	2	2	2
30– 60	6	8	8
60– 90	21	29	29
90–120	31	60	60
120–150	13	73	73
150–180	15	88	88
180–210	4	92	92
210–240	3	95	95
240–270	5	100	100

[a] After taking 50 more observations.

2.3.3. South Dedwas

Here radon holes were arranged in two lines of 5 holes each, separated by 150 m downdip. The joint data fell into two lognormal distributions (Fig. 9), but when plotted for the two lines separately, the first line showed two lognormal distributions (Fig. 9a) and the one downdip gave a single lognormal distribution (Fig. 9b). Because of the fact noticed at Delhi that even if a single hole in the series shows two distributions the joint data, although the rest of holes may have single distribution, will show overall two distributions, we have to treat each hole individually to isolate the one responsible for two distributions and to confirm if more than one hole is responsible for the two distributions. The frequency distributions are given in Tables VI, VIa, and VIb.

2.3.4. Pur Dariba

In this area all the radon values given in Table VII were distributed lognormally (Fig. 10).

2.3.5. Siswali

The data in this area are given in Table VIII. The grouped data shows two lognormal distributions (Fig. 11).

2.3.6. Sior

Frequency distributions of the radon values of this area are shown in Table IX. The grouped data shows two lognormal populations of radon (Fig. 12).

TABLE VII. COMBINED FREQUENCY DISTRIBUTION OF RADON VALUES IN TEN AUGER HOLES

AREA : Rajasthan (Purdariba) February to March 1972

(1) Average U_3O_8 in Soil : 2.3 ppm in the range 2.0 to 2.8 ppm.
(2) Range of radon values : 0.27 to 1.9 pCi/cm^3.
(3) Calibration factor : 1000 counts/min = 6 pCi/cm^3.

Class Interval (counts/min)	Frequency	Cum. Frequency	% Cum. Probability
30- 60	5	5	5
60- 90	16	21	21
90-120	33	54	54
120-150	22	76	76
150-180	9	85	85
180-210	6	91	91
210-240	3	94	94
240-270	4	98	98
270-300	1	99	99
300-330	1	100	100

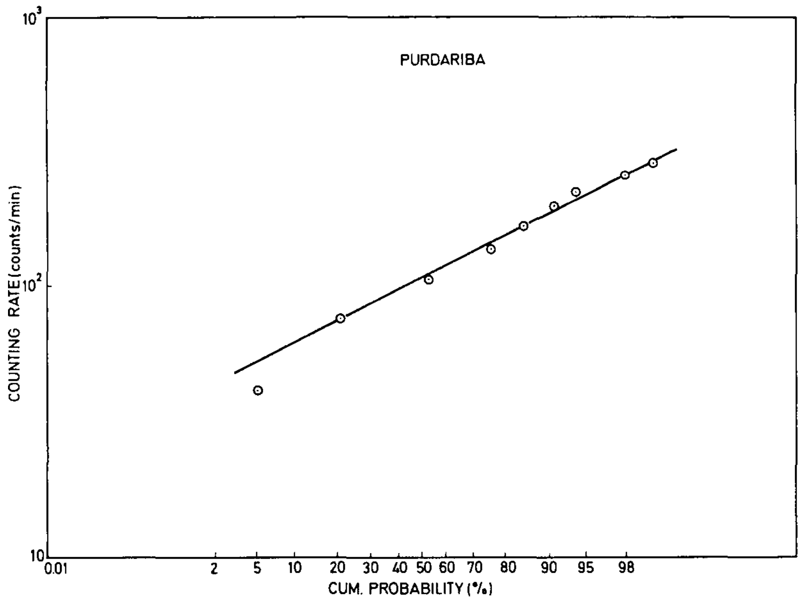

FIG.10. Log-probability plot of radon values at Purdariba, Distr. Bhilwara, Rajasthan, showing a single lognormal distribution.

TABLE VIII. FREQUENCY DISTRIBUTION OF RADON VALUES

AREA Rajasthan (Siswali) June to September 1971

(1) Average U_3O_8 in Soil : 3.7 ppm in the range 3 to 5 ppm.
(2) Range of radon values : 0.25 to 9.25 pCi/cm^3.
Four boreholes have been drilled up to a max. depth of 86.7 m. Only one hole gave radioactivity beyond 25.8 m with an average of 0.020% $\underline{e}U_3O_8$.

Class Intervals (pCi/cm^3)	Frequency				
	Hole No. 1	2	3	4	5
0 - 0.5	8	9	3	5	4
0.5 - 1.0	8	5	5	6	6
1.0 - 1.5	7	1	4	2	3
1.5 - 2.0	7	2	3	4	3
2.0 - 2.5	4	3	4	2	6
2.5 - 3.0	4	2	4	7	4
3.0 - 3.5	2	2	3	1	6
3.5 - 4.0	4	4	2	3	2
4.0 - 4.5	1	4	-	0	3
4.5 - 5.0	2	1	-	1	1
5.0 - 5.5	-	-	-	3	-
5.5 - 6.0	-	-	-	2	-
6 0 - 9.5	-	-	-	7	-

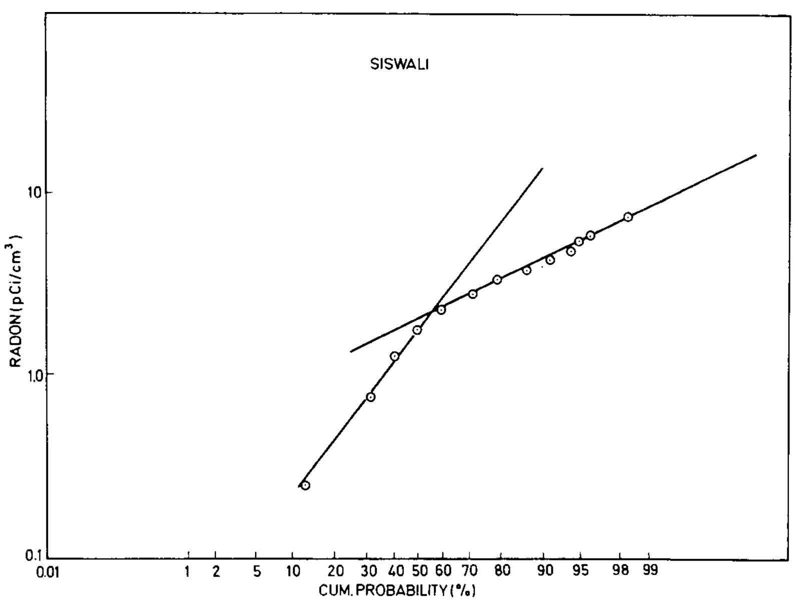

FIG. 11. Log-probability plot of radon values at Siswali, Khetri area, Distr. Jhunjhunu, Rajasthan, showing two lognormal distributions.

TABLE IX. FREQUENCY DISTRIBUTION OF RADON VALUES

AREA Rajasthan (Sior) **July to October 1971**

(1) Average U_3O_8 in Soil : 3.8 ppm. in the range 3 to 5 ppm.
(2) Range of radon values : 0.25 to 6.2 pCi/cm^3.
One borehole has been drilled up to 28.6 meters; has shown radioactivity beyond 14.7 meters with an average of 0.016% $\underline{e}U_3O_8$.

Class Interval (pCi/cm^3)	Frequency				
	Hole Nos. 1	2	3	4	5
0 - 0.5	4	5	7	6	7
0.5 - 1.0	3	10	4	11	4
1.0 - 1.5	3	7	3	4	6
1.5 - 2.0	7	5	4	5	7
2.0 - 2.5	10	8	7	2	6
2.5 - 3.0	10	12	7	0	9
3.0 - 3.5	6	2	8	0	4
3.5 - 4.0	3	0	4	0	1
4.0 - 4.5	1	0	2	0	1
4.5 - 5.0	0	0	0	0	0
5.0 - 5.5	0	0	1	0	0
5.5 - 6.0	0	0	1	0	0
6.0 - 6.5	1	0	0	0	0

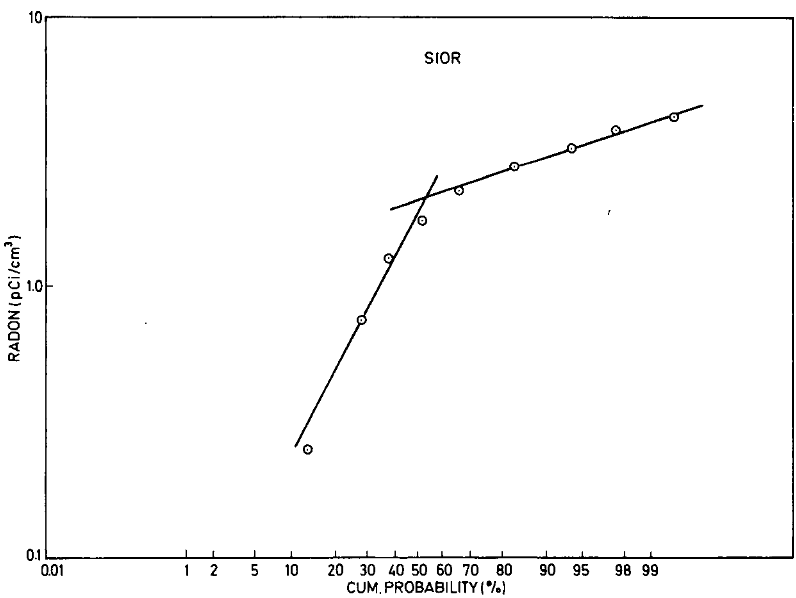

FIG. 12. Log-probability plot of radon values at Sior, Khetri area, Distr. Jhunjhunu, Rajasthan, showing two lognormal distributions.

2.4. Known geological differences

The area for many miles around Delhi is known to be unmineralized. Both the sites at the laboratory ground and Mehrauli are situated within this area.

Banera, North and South Dedwas and Pur Dariba lie in Bhilwara district about 576 km southwest of Delhi. In these areas Airborne Mineral Survey and Exploration, a wing of the Geological Survey of India, are drilling for copper, lead and zinc. Gamma logging of their drill holes has shown a radioactivity equivalent of < 100 ppm. As finer logging was not considered necessary in exploration for uranium, subsequent lithological logging showed zones of radioactivity at various depths varying from 25-50 ppm, compared with the soil activity of 5 ppm of uranium. Distribution of the activity of thorium and uranium is under study.

Sior and Siswali (Khetri area) are situated nearly 180 km southwest of Delhi and 30 km from each other. The region is known to be mineralized with some massive copper mineralization with scattered mineralized bodies around it which were found to be associated with poor and sporadic occurrences of uranium. The Department of Atomic Energy has drilled at the two above-mentioned sites and bands of uranium 20-40 cm thin with uranium concentration up to 200-300 ppm have been encountered at depths of 15-25 m.

3. TEST EXPERIMENT

To test if the two lognormal distributions were caused by the appearance of radon in the topsoil from a richer zone below, or by having its own variations with a different mean and standard deviation and not being exposed to the same meteorological influences as the topsoil, an experiment was conducted in the laboratory ground. One hole was dug and loaded with 1 μCi radium chloride solution and other holes were dug around it at distances of 1, 2, 3 and 4 ft. After several weeks of observation in individual holes, the data for each hole was statistically treated and plotted. All holes which were at a distance of 1 ft from the loaded hole showed two distributions while those beyond this distance showed a single lognormal distribution. This suggested that the two holes (E and I) in the earlier measurement in the above-mentioned laboratory ground which gave two distributions might be receiving radon from a buried dump of discarded radioactive samples. The place is being dug up to see if any material is dumped there. If it turns out to be so it will confirm the conclusion that the two distributions appear when radon from a buried body gets into the topsoil.

4. CONCLUSIONS

These investigations do not seem to have reached the stage where firm conclusions can be drawn. From the information gathered so far it can be said that (1) unmineralized areas show a single lognormal distribution of radon values, (2) mineralized areas having uranium as an accessory might produce two distinct lognormal distributions, (3) in South Dedwas the line of holes further downdip shows a single distribution whereas the top line

shows two distributions. This can mean either that the mineralization has ended before the downdip line is reached or that the soil cover is too thick for any influence to be felt in the topsoil over this line and (4) from the test experiment one might conclude that radon getting into the soil from a concentrated source may give rise to two distinct lognormal distributions.

Many more areas, both mineralized and unmineralized, must be investigated to show if the results hold consistently. At present it is just an assumption that radon entering into the topsoil from an underlying source produces two lognormal distributions. In what manner it distributes itself to produce such an effect and retain its identity is not clear. That there might not be other conditions and factors which can produce a similar effect cannot be said with certainty.

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DISCUSSION

H.H. ADLER: I would like to raise the question of what one might expect if one were making radon measurements over an area that was known to be petroleum-bearing. For example, over a salt dome that had petroleum accumulations around the periphery and was essentially a point source so that faulting or other structural features would possibly be bringing out radon which is known to be associated with the radium accumulating with petroleum.

A.S. BHATNAGAR: We have not carried out radon measurements in such an area but we have carried out radioactivity measurements in such an area, and we find that as one approaches a deposit, there is a slight increase in radioactivity which then drops down in the centre and only increases as the periphery is again approached.

M. DALL'AGLIO: What, in your opinion, is the factor that causes the lognormal distribution.

A.S. BHATNAGAR: We think it is the radon that gets into the upper soil from below which has its own distribution. We are unable to separate the two, but it should have its own mean value and standard deviation; but the result is that, when the two samples come together, the double distribution is produced.

H.H. ADLER: You mentioned that you allowed a 24-h time interval between pumping and collection. Have you established that this is a minimum or optimum time? In some experiments that have been conducted in the United States of America, the results seem to indicate a rather extensive exhaustion of the radon in the surface material, so that there is a recovery time that has to be considered. What do you consider as a minimum time?

A.S. BHATNAGAR: Stable conditions appear much earlier but to be a little cautious we allow a little more time than would be necessary. The thing is that we do not use any pump to suck radon. We only have what we call the chloroform bellows which produces no turbulence and merely circulates the air between the detector and the hole so that it does not draw any air from the rest of the soil.

A.G. DARNLEY: Do I understand you correctly, Mr. Bhatnagar, that you are saying that where there is mineralization there is a bimodal distribution of measured concentrations? It is interesting that this seems to be a common symptom of mineralization within geochemical sample populations. For example, it is shown in plots of the uranium distribution in both the syenites of the Bancroft area, and the Matinenda quartzite in the Elliot Lake region; it is shown by nickel distribution in ultrabasics in Canada. Rock units that are mineralized show a bimodal or multimodal distribution, whereas units that are not show a single-mode population.

A.S. BHATNAGAR: Yes. It is essentially a bimodal distribution with the difference that in the case of radon, being in the gaseous phase, there is a good deal of intermingling of the two populations, and the bimodal character is suppressed and does not appear distinctly in a straight frequency plot but can be inferred in a cumulative frequency plot as a two lognormal distribution.

RADON MEASUREMENT IN URANIUM PROSPECTING

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Abstract

RADON MEASUREMENT IN URANIUM PROSPECTING.

The nature and origin of the three naturally occurring radon isotopes is discussed together with the processes by which they migrate from the parent mineral through rock, soil and water. Attention is drawn to the effects of migration of soil profile, ground saturation and meteorological conditions and to the factors affecting the occurrence of radon in lakes and streams. Details are given of the methods used to detect radon in soil and water and a survey made of instruments currently in production. These include probe and pump-type monitors with alpha-sensitive phosphors, and ion chamber detectors. Considerations governing the use of radon measurement as a primary and secondary uranium prospecting technique are presented and examples are given of radon in soil surveys carried out in the United Kingdom. Progress in the future will rely on operational experience in different environments and modifications to specific features of instrumentation suggested by local needs.

1. INTRODUCTION

The possibility of using radon measurement as a uranium prospecting technique was first suggested by Behounek in 1927 after studying the anomalous radioactivity he found in springs, soils and the atmosphere around the uranium deposits of Joachimsthal, Czechoslovakia [1]. The original attempts to develop a field prospecting method based on determining the concentration of radon in soil air were carried out in the Soviet Union during the early thirties [2, 3] and have been increasingly applied in that country ever since. Further studies of the geochemistry of radon were stimulated by the extensive uranium exploration programs undertaken on a world-wide basis since 1945. Prospecting techniques based on this work were not widely used prior to 1960 as the discovery rate of uranium deposits could be maintained by the application of surface gamma radioactivity measurement. The discovery of new ore bodies in present and future uranium exploration is likely to prove more difficult, however, and it has become necessary to investigate and improve methods, including those involving radon measurement, which show promise of indicating the location of concentrations of uranium having little or no surface gamma expression.

Being a noble gas, radon does not combine with other elements, a property which facilitates its free migration through pore spaces in rock and soil and its dispersion over considerable distances by groundwater and surface water. It occurs naturally as three isotopes with the mass numbers 222, 220 and 219, which are members of the ^{238}U, ^{232}Th and ^{235}U decay series respectively. After formation by radioactive decay, a radon atom diffuses through the enclosing mineral, but its escape from the mineral grain is unlikely unless the parent radium is very close to the grain

surface. This latter condition will be realised if the grain is small or if the radium has been concentrated in a thin crust at the surface of the grain by secondary alteration processes such as hydrothermal activity or weathering. Evidence of the latter mechanism of release has been produced by Starik and Melikova [4] who showed that weathered samples tend to give off more radon than fresh material and that primary uranium minerals are less productive than their secondary derivatives.

Having escaped from a mineral, radon will diffuse through the ground air or groundwater present in pore spaces and, to a limited extent, become dissolved in the water. At this stage, the relative half-lives of the three isotopes become important. Radon 222 has a half-life (3.8 d) greatly in excess of ^{220}Rn (52 s) and ^{219}Rn (3.9 s) and this enables it to migrate considerably further than the two shorter-lived isotopes. Tanner [5] estimates that ^{222}Rn diffusing from a plane source through dry sand will travel approximately 7 m before suffering a hundred-fold diminution in concentration by radioactive decay. The corresponding diffusion lengths for ^{220}Rn and ^{219}Rn are 2 cm and 6 mm respectively. As Bulashevich [6] has shown that the concentration of radon in ground air is distributed in depth approximately according to a diffusion model, it is unlikely that the thorium-derived isotope will be present remote from the immediate vicinity of thorium minerals.

Diffusion is not, however, the only means by which radon is transported in a dry medium. In arid areas with little or no topsoil there is almost complete continuity between ground and atmospheric air and the former comes under the influence of meteorological variables (Fig. 1). Low barometric pressure and strong winds tend to draw ground air out of the pore spaces and fractures of the near-surface layers, thus reducing the radon concentration within them and causing an upward movement of the gas from depth. Calm anticyclonic conditions on the other hand reduce the rate of radon escape to atmosphere and result in a build-up within the ground. Rainfall also restricts the upward flow of radon but has varying effects depending upon the soil profiles. Where soil is absent the rainwater penetrates deeply and seals off the pore spaces in depth, thus producing a temporary reduction in near-surface radon concentration. A well-developed humic topsoil, however, absorbs most of the rainfall itself and forms an impermeable but thin cover beneath which the radon accumulates. In these conditions near-surface radon concentrations are high and can lead to the development of surface gamma anomalies (Fig. 2).

Complete saturation of the ground greatly reduces the distance over which radon can diffuse. The diffusion length of ^{222}Rn in water is only about 10 cm [5] and it is evident that any significant migration will be dependent on the flow of the containing groundwater. The many radon springs found around the West of England granites bear testimony to the efficacy of this mode of transport but, in general, groundwater flow is less than 1 ft/d which implies that the range of radon migration in saturated ground is limited.

Recent work in Canada [7] shows that most of the radon content of surface waters is derived either from radium adsorbed on the bottom sediment or from springs feeding the lakes and streams. The concentration falls off with distance from these sources. A similar effect is caused by increases in water flow and turbulence. A rise in alkalinity, on the other hand, tends to be associated with augmented radon values.

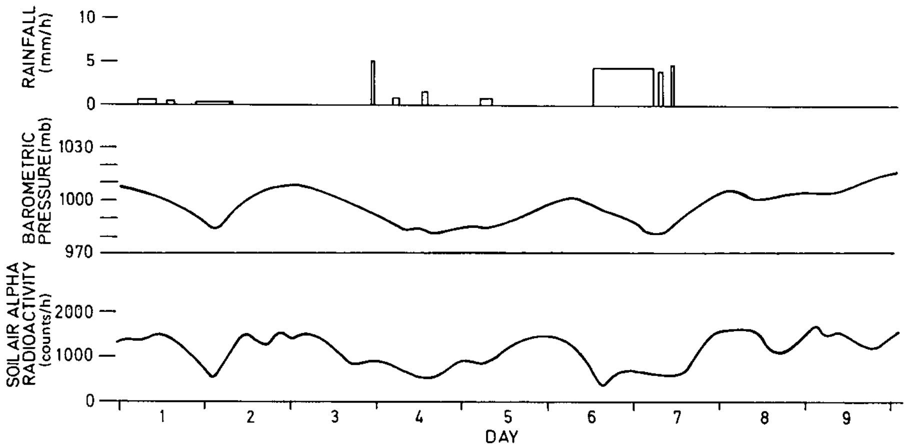

FIG.1. The effects of atmospheric conditions on radon concentration in soil air: Absence of humic topsoil gives rise to sympathetic variation of soil air radon concentration with barometric pressure. Heavy rainfall causes marked depression in concentration on days 6-7.

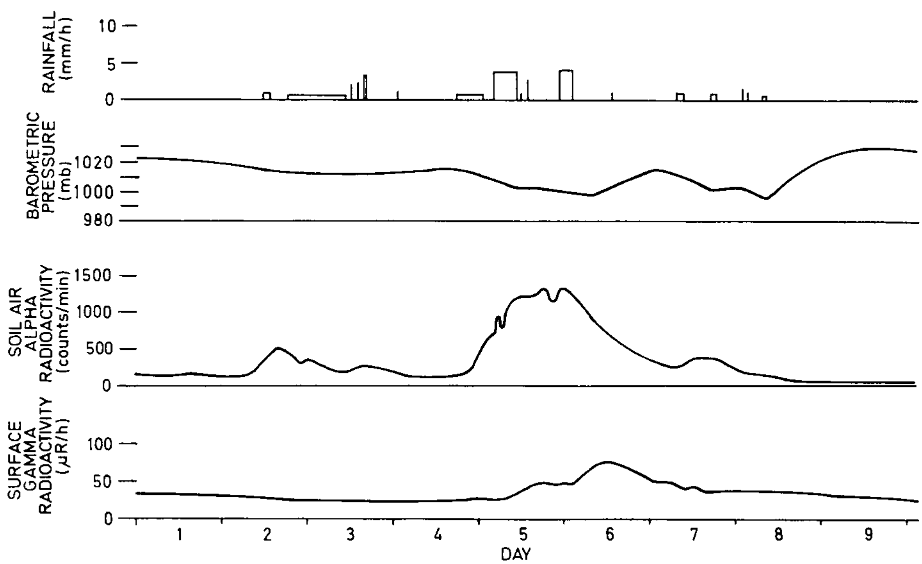

FIG.2. The effects of atmospheric conditions on radon concentration in soil air: When saturated by rainwater, humic topsoil seals off escape of radon to atmosphere and causes build-up of soil air radon concentration. If this is sufficiently prolonged, radon decays into gamma-emitting isotopes, producing rise in surface gamma activity. Effect disappears as rain ceases and ground dries.

To sum up, it must be emphasized that radon prospecting is concerned with a dynamic system depending upon a number of variables and it is therefore hazardous to attempt to arrive at any absolute basis for the interpretation of results.

2. METHODS OF DETECTION

All radon prospecting techniques are based on the natural alpha radioactivity of radon and its immediate daughter elements, and the equipment employed to date detects either the alpha emissions themselves or the degree of ionization caused by these emissions. By far the majority of methods measure the alpha activity and incorporate detecting chambers coated with the alpha-sensitive phosphor, silver-activated zinc sulphide. Radon-bearing soil gas, or gas samples stripped from water, are drawn into these by some form of pneumatic system and alpha radioactivities determined by viewing the scintillations produced in the phosphor by means of a photomultiplier. Signals are fed to a ratemeter or scaler.

Whilst in the detecting chamber the gaseous radon decays to solid alpha-emitting daughter elements, principally ^{218}Po and ^{214}Bi, which tend to adhere to the walls of the detector. These are only partially removed when the chamber is flushed with atmospheric air between measurements so that, as successive samples are introduced, there is a build-up of residual alpha contamination which reduces the statistical accuracy of the determinations. This can be countered only by changing the detector and it is important that the design of the detector allows this to be effected with the minimum of difficulty.

The methods of obtaining the sample and introducing it into the measuring chamber vary with individual equipment but, broadly speaking, soil air measurement instruments can be classified into alpha probes and pump monitors, whilst radon in water determinations can be made only with pump monitors. Almost all equipment is capable of being adapted to either role.

The alpha probe illustrated in Fig. 3 is designed to take soil air measurements in 60 $\times$ 4 cm sampling holes made with a special bar which is driven into the ground and then withdrawn. Withdrawal of the tool draws air from the surrounding soil into the hole which is immediately cased with a tube. The probe is inserted in the tube and pushed to the bottom; the plunger-like action forcing the air in the tube into the detector chamber of the probe. This contains a centrally mounted perspex cylinder coated with zinc sulphide, and scintillations within the phosphor are internally reflected up the cylinder to an optically coupled photomultiplier. Each scintillation pulse is counted on a timer-controlled scaling unit mounted at the upper end of the probe. This equipment measures the total alpha radioactivity of radon and its daughter elements in unfiltered soil air, but contamination is kept to a minimum by wrapping the cylindrical detector in aluminium-coated plastic foil.

Pump monitors, when used to measure radon in soil air, also require sampling holes. These can vary in size from 51$\times$1.2 cm to 2.5 m$\times$10 cm, the smaller ones being made with a bar whilst larger holes are drilled with a power auger. The smaller holes are generally made for measurement with lightweight portable instruments, one model of which carries

FIG.3. Alpha-probe radon monitor being inserted in cased sampling hole made with hammer bar (left).

out the measurements on soil air which is drawn into the hole when the bar is withdrawn. With this equipment the hole is capped and the soil air sample sucked into the detecting chamber of the monitor through a rubber tube fitted with a squeeze bulb pump. A second tube serves as a return passage from the chamber to the hole, thus providing a closed system through which the air is circulated until a uniform air-radon mixture is achieved. The internal walls of the cylindrical plastic detecting chamber are coated with zinc sulphide and scintillations produced on them are viewed by a photomultiplier positioned opposite the lower open end. Alpha scintillation pulses are recorded on a timer-controlled scaler.

Most other portable pump monitors have an open pneumatic cycle, the soil air being drawn from the sampling hole through the measuring chamber and usually exhausted to atmosphere. Such instruments not only monitor the soil air in the hole but, in addition, draw in a considerable volume from the pore spaces in the surrounding soil. Suction is achieved either by evacuating the system and then allowing it to refill with soil air, or by continuous operation of a hand pump. In the latter case the scintillation pulses are fed to a ratemeter and pumping continued until a constant meter deflection is obtained. These types of pneumatic systems tend to draw in dust and moisture and require efficient filters which also remove most of the solid radon daughter elements. This gives a lower alpha count rate than unfiltered air but it is claimed that residual contamination is also reduced.

Larger, vehicle-mounted equipment employing power augers also usually rely on an open-cycle, continuously pumped system. Before pumping, the holes are sealed against ingress of atmospheric air by means of an inflatable rubber gasket through which the outlet pipe projects. The output from the photomultipliers is usually displayed on a recording ratemeter.

In some portable pump-type monitors the phosphor-lined detecting chamber is replaced with an ion chamber. This consists of a detachable outer stainless steel shell with an insulated central wire electrode, and the value recorded is the mean current flowing across the chamber owing to ionization of the contained air by the alpha radioactivity of the radon. The principal advantages claimed for this method are that low residual currents can be "backed off" on the current meter display and that heavy contamination can be reduced to manageable proportions by wiping the interior of the chamber with a tissue.

All radon in water determinations are necessarily made in closed cycle or vacuum systems. Water samples are collected in 1 - 2 litre containers and the gas content stripped by bubbling atmospheric air through the sample. The efficiency of the method depends upon the surface area of the bubbles and good results are obtainable by introducing the air through a very fine fritted glass filter. The stripped gas-air mixture can then be monitored in almost any of the soil air equipment.

3. FIELD APPLICATIONS

Radon in ground air surveys have their greatest potential value in areas where promising indications of uranium mineralization already exist but in which the bedrock gamma radioactivity is masked by a layer of inactive overburden. Ground air radon determinations are most effective where this layer is of dry porous material and less than 10 m thick; but recent reports from Canada indicate that radon in groundwater measurements have also proved effective in areas where bedrock uranium mineralization is overlain by saturated drift.

Up to the present time most applications have relied on the use of ground air techniques. These have been employed extensively in the loess-covered areas of Eastern Europe and Asia, while considerable efforts have been made over a number of years to apply the method in Western North America, with the object of locating deeply buried uranium mineralization within the Tertiary sandstone basins of that region. This work has demonstrated that a system based on vehicle-mounted pump-type monitors, drawing air samples from 2 m$\times$10 cm holes, is able to delineate anomalous areas which reflect the pattern of uranium mineralization 60 - 100 m below the surface. It seems unlikely that such conditions are due to the direct migration of radon from the ore bodies to the surface. More probably they are due to radon emanating from secondary uranium dispersion haloes around the mineralization. In this area the presence of thorium-bearing resistates within the sandstones gives rise to considerable concentrations of thoron (^{220}Rn) within the ground air and it has been found necessary to retain the sample within the detecting chamber for several thoron half-lives (10 - 12 min) before taking a measurement, in order to allow time for the thoron to decay.

Since this Western-USA-type of sandstone mineralization may extend laterally over several miles, it forms a suitable target for regional surveys of radon in ground air. Such a survey was carried out by Stevens, Rouse and De Voto [8] in the Denver Basin. Measurements were made on a one mile square grid in 4-ft-deep sampling holes and anomalies detected which led to the discovery of non-outcropping sandstone uranium mineralization.

Radon in water determinations have been used as a regional exploration technique in various parts of the Canadian Shield [9, 10]. At Bancroft, Ontario, Smith was able to delineate the zone of uranium mineralization from the disposition of values obtained on surface water samples from lakes and streams, whilst Dyck showed that statistical analysis of similar data provided equally useful information in the Beaverlodge area.

Regional radon exploration surveys have therefore been shown to be practicable; but to date few of these have been conducted, most radon work having been at closely spaced sampling intervals in known areas of uranium mineralization, with the aim of examining the potential of structures and the establishment of extensions to existing ore bodies. Within the areas of vein-type mineralization of Western Europe, ground air radon traverses and grids are based commonly on portable probe and pump monitor measurements taken 5 - 10 m apart.

An example of this type of survey carried out by the Institute of Geological Sciences in Orkney, Scotland is shown in Fig. 4. Here, surface reconnaissance had located a 100 × background gamma anomaly where a fault between Old Red Sandstone conglomerates and flagstones was exposed in a stream section. Attempts to trace the anomaly by radiometric survey on either side of the stream revealed only a few small gamma anomalies none of which was located more than 50 m from the original discovery. Ground air radon measurements taken at 6-m intervals with a type M. 8560 probe showed the presence of anomalous radon concentrations over a distance of more than 300 m along the fault, in a cover of glacial drift up to 2 m thick. Subsequent drilling proved uranium mineralization along the fault structure and extending a short distance into the conglomerates. The tendency for higher-than-normal radon concentrations to occur over the conglomerate may be ascribed to the presence of weak uranium mineralization and also to the greater porosity of the sediments.

4. CONCLUSIONS AND FUTURE DEVELOPMENTS

The measurement of radon concentrations in ground air and surface waters is now an established uranium exploration technique. In the simple circumstances of a thin layer of dry arenaceous material overlying bedrock of low relief, the radon pattern obtained is a direct guide to the distribution of sub-outcropping uranium mineralization. Such specific and precise delineation of sub-outcropping uranium is outside the capability of any other technique. Increases in the thickness, inhomogeneity and water content of the overburden, combined with groundwater flow, tend to distort the relationships between mineralization and the resulting alpha anomaly and can even render the radon monitoring results meaningless. It is evident that, as with other geochemical techniques, an orientation study is a prerequisite of the application of the radon method in a given area.

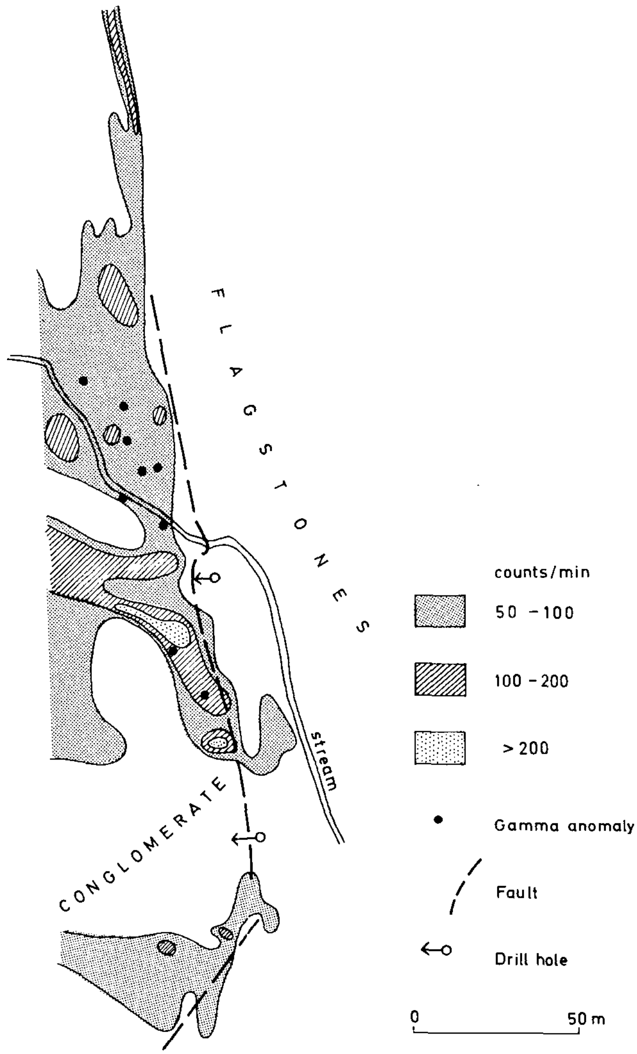

FIG.4. Distribution of soil air alpha radioactivity and surface gamma radioactivity along Mill of Cairston Fault, Orkney, Scotland.

All the equipment currently marketed is capable of giving useful results if properly used. The probe-type equipment is able to operate more satisfactorily in wet ground but tends to be less sensitive than the pump monitors. For practical purposes, however, this has not been found to be a shortcoming. Generally speaking, the most meaningful measurements are obtained in the deepest sampling holes and in this respect the vehicle-borne equipment, employing power augers, necessarily has an advantage over the smaller portable instruments.

The principal disadvantage of all radon equipment, particularly those based upon zinc sulphide phosphors, lies in their susceptibility to contamination by radon daughter elements. The detector can be made more resistant to this effect by covering it with aluminized plastic foil, as in the type M. 8560, but this reduces the sensitivity. A solution to the contamination problem may lie in alpha spectrometric determinations, employing semiconductor detectors, which should provide for the counting of only those alpha particles derived from ^{222}Rn. If this does not prove practical, recourse will have to be made to the development of more easily changed phosphors, perhaps mounted on rolls of film.

In conclusion, it should be stressed that understanding and development of the radon prospecting technique can best be expedited by an increasing flow of publications from practising organizations.

ACKNOWLEDGEMENT

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DISCUSSION

M. MATOLÍN: I should like to ask Mr. Ostle whether they have done any investigation on the dependence of the values observed on the depth of the hole. As far as I understand from your paper, the first radon monitor was used in holes of 60 m depth.

D. OSTLE: We have not, of course, done very much work of this kind, principally because we have developed a standard system which is not really amenable to use in holes of varying depth, as it cannot go beyond the length of the probe itself. In our early investigations we did make this kind of depth measurement and found that in general there is an advantage in using deeper holes. It is a question of cost and of speed of operation and we arrived at what we felt was an optimum operational figure. This will not apply in every case, of course. It is not a very difficult matter to develop equipment which will monitor deep holes if it is found essential to get beneath an impermeable cover.

J. F. DAVIS: We have run several thousand tests utilizing auger-mounted equipment. It has been our experience that the atmospheric dilution, rather than contamination, seems to be a critical factor. It seems as though holes on the order of two metres have given us the best results. With the power auger equipment we can run approximately 20 to 25 tests per day with one man, so that the cost has not been too great. I think the dilution in our experience has been the deciding factor to convince us to go to the slightly higher cost of using the auger-mounted equipment to get greater depth.

D. OSTLE: I can understand that you would have had this problem with the system you are employing, but, of course, by using the probe, we do not pump air out of the hole. The possibility of drawing atmospheric air into a pumped hole when it is of shallow depth is one of the factors that must be considered. If you pump, then I think it is necessary to increase the depth of the hole.

M. MOREAU: In France we use radon prospection as a tactical tool. We use it very little in regional exploration. I would like to know if the results obtained by Mr. Ostle in the United States of America in very deep sandstone were obtained in a virgin area or whether earlier exploratory work had taken place, such as drilling?

D. OSTLE: Thanks to our US colleagues, there was a knowledge from drilling of the disposition of uranium in depth, but in fact there had not been any mining carried out in the area at that point. So it was virgin from that point of view.

J. A. FERNANDEZ POLO: I would like to give you some information obtained in Spain.

In the Ciudad Rodrigo area, we measured radon in bore-holes and found the internal air was contaminated; we observed variations from one day to another. In this area, when we tried to carry out systematic measurements based on emanation, the results were completely scattered and were not to my mind indicative. On the other hand, the great influence exercised by climatic variations on present tests being carried out in Soria, which is in the centre of the country and has considerable climatic variations from very dry to very wet, and from winter to summer temperatures, have caused us to find differences of from 2 to 3 up to even 14 to 15 times the background. We do not feel that these measurements are either expressive of proximity to mineralized bodies or to anything else.

D. OSTLE: Well, I would only like to repeat what I said on starting that there is quite a body of theoretical information, which would suggest that we should never try to use radon as a method at all. But it does work, in particular circumstances. Like any other method it has to be considered very carefully by a geologist in relation to structure, lithology, and even

possibly the volcanic history of an area. We do find that concentrations of radon present some problems of interpretation in areas of warm springs. The radon results have to be viewed against a whole background of geological data. Undoubtedly, atmospheric conditions have an effect, and this is why I said that it is hazardous to try to arrive at any absolute basis for the comparison of radon results. One even has to work on almost an hour-to-hour basis in meteorologically unstable areas to ensure that comparisons between values are valid. But there are some enormous problems of this kind.

H. H. ADLER: In regard to radon in water I think, from reading of Canadian experience, that they get what they assume to be anomalies at levels of a few pCi/l of radon concentration in waters and can apparently use these effectively as an indicator of nearness to a uranium source. This is an extremely low level of concentration. I know there is a body of opinion in the United States that indicates that anything less than say 1000 or 10 000 pCi/l in groundwater, not surface water, but in subsurface water is just normal. We have areas, not known to be mineralized, with a radon concentration which seems to be anomalous at 16 000 - 25 000 pCi/l. Even beyond that we have an area in the Eastern United States in metamorphic granitic-type rocks in which we have not yet found or have any indication of any quantity of uranium. Here, over almost a hundred miles or so we get anomalies in well waters that go up to the hundred thousands pCi/l, and this is not understood, but neither is it obvious that these anomalies are related to ore concentrations. The evaluation of radon in an unexplored or new area is a very tricky business, particularly in water. It may not be as difficult in air.

In regard to the measurement of radon as an emanometry technique, do you measure absolute concentrations or do you just record your values as counts per minute? If it is the latter, would it not be better to standardize on something, for example, to make quantitative measurements in terms of pCi/l. One could then get a cross reference from one type of terrain to another whereas count/minute readings are almost meaningless.

D. OSTLE: I agree with Mr. Adler's point, that a dissemination of results has this prerequisite measurement of units. But we have not standardized so far and I think it is probably due to the emergence of radon from being a purely local technique to being a possible regional method. Once this has happened, we have to standardize.

H. H. ADLER: Using it as a prospecting technique, I can see where you go into the field with an instrument and you yourself set up a standard so that you can correlate your counts/min values from district to district and you can prospect on this basis very effectively. But, if you try to convey your information to someone else in terms of his experience, he is lost and I think this is where one ought to try to encourage standardization.

A. G. DARNLEY: I would again like to support the concept of standard measuring units. I think it could be one of the most useful things to come out of this meeting if we could start to make some progress on the matter of standardizing all measurements with which we are concerned. I think we are all aware we are at the beginning of a new phase of exploration relating to radioactive materials and now is the time to try and come up with some recommendations which people will follow. If we do not make the effort now, it is going to be too late.

THE DISCOVERY AND INVESTIGATION OF BLIND DEPOSITS OF URANIUM*

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Abstract

THE DISCOVERY AND INVESTIGATION OF BLIND DEPOSITS OF URANIUM.

In many parts of the world there are no more outcropping deposits, but it is probable that blind deposits exist. Such deposits are located using methods very different from conventional ones. To discover economic but blind uranium deposits, the prospective areas should first be examined by metallogenic analysis.

In the case of endogenetic deposits, structural maps, lithological maps and maps showing the level of erosion must be prepared. Following this the dispersion haloes of U, Hg, I, Li and other chemical elements and the alteration zones of the country rock should be investigated in relation to geology and structure. In the case of exogenetic deposits, geological maps and maps of the extent of erosion of the overall petrogenic complex are drawn up. Subsequently, maps showing the distribution of the facies and palaeogeographical reconstruction are produced. The palaeorelief, circulation of subterranean water, location of the water table and sedimentological structures are studied, and the position of the shore line and the direction in which clastic material is transported are determined. In so far as the results of these investigations indicate the possible existence of uranium-bearing petrogenic complexes, research is then carried out on the dispersion of U, Ra and Rn in the water, alluvium and rocks. The radioactive pattern associated with the lithostratigraphic column of the rocks is determined. Finally, an attempt is made to discover the depth of host structures by means of geophysical prospecting, and also any evidence of uranium recycling. On the basis of such results prognostic maps are compiled and the work required to discover and investigate a blind deposit of uranium is determined. Such work may consist of drilling, mining exploration and associated operations.

* Only the abstract is printed here, as the author was unable to attend the meeting. However, the paper was open to discussion. Requests for copies of this paper should be addressed direct to the author.

PANEL REPORTS

PANEL REPORTS

As defined by the Agency, Panels are composed of a small group of experts in their individual capacities and designated by the Director General to advise him on specific subjects or questions and to suggest future Agency policy on these subjects.

The Panel under its Chairman was asked to advise on the general subjects outlined in the Foreword of this publication but, in order to assist the Panel, the Secretariat drew up seven short documents as a basis for Panel discussions. These documents were designed to highlight the main topics and problems which the Agency meets in uranium exploration advisory work.

A summary of the Secretariat documents and the reports prepared by the Panel in response to these documents are published in the following section in the belief that the reports are of wide interest and utility.

1. GENERAL POLICY ON FUTURE EXPLORATION REQUIREMENTS

SECRETARIAT REQUEST TO THE PANEL

Apart from those countries where national organizations control uranium exploration and production, the vast majority of the uranium to be utilized in nuclear power stations over the next twenty years will be produced by commerical organizations. World demand and supply, the market price of uranium and the competitive situation of an organization will determine the financial status of such organizations and this in turn will largely control the amount of funds which they make available for exploration. The strong possibility of periods of slump and boom in uranium exploration can be foreseen over the next twenty years.

The Panel is invited to discuss this situation and to advise the Agency on what its policy (as an international advisory organization) should be on the subject of future exploration requirements.

DISCUSSION

A.G. DARNLEY: Do we have a figure for the cost of discovery of a pound of uranium, in the United States of America for example, during recent years?

R.D. NININGER: We have an estimate which we use to project the cost of discovery of our potential resources, which is in the range of 80 cents to $1 per pound, so that, if the exploration costs alone in our area were substantially larger than in the past, it would not be a major impediment to increasing our production capacity. The big financial investment will be in the development of the deposits, the mining plant and the milling plant. I suspect it would be almost impossible to come up with a world figure for exploration cost – it varies so much from one deposit to another, let alone from one country to another.

J.F. DAVIS: The big detriment to exploration as we see it is the present soft market for uranium, which of course has depressed the price, and I think most financial people obviously just will not put up the money if the cost of production is not going to give them a good return on their investment. By the time they look at the present-day prices of uranium, and the associated production cost, it just does not look like an attractive investment, even though the exploration investment is a small part of the total cost.

S.H.U. BOWIE (Chairman): I have also attempted to get a world figure for uranium cost, and by that I mean a realistic figure, which takes into account most of the effort that has been put in by government organizations, as well as by private industry, and the figure is not very different from the one Mr. Nininger has just given us. It is of the order of $1 per pound of oxide, and I think that this is the sort of figure we ought to perhaps keep at the back of our mind – it might, of course, be less than this in certain territories and in other territories it might be appreciably more, but I have little doubt that the figure is of the right order.

J. BRINCK: You are stating a price of \$1 for prospecting for 1 lb of yellow cake U_3O_8. Now, does this refer to reserves in the economic sense – reserves that can be mined at this moment – or is this based on the \$10 target price which is always used for classification purposes?

S.H.U. BOWIE: The figure is one which relates to reserves as presently recognized, not to potential. I should say there is no other definition of reserves to an economic geologist – other than that which is mineable at a profit at the present moment.

R.D. NININGER: I might emphasize that a little more. We are having this problem in the USA today. We use what we call an \$8 reserve for our first estimate and we also estimate a reserve at \$10. The ENEA and the IAEA use \$10. We talk about world reserves being some one million metric tons at \$10, but the problem is that the price is not \$10, the price is not \$8, the price is not even \$7 – it is more like \$6, so that we do not have these reserves. We do have mineralized material which might be a reserve at those higher prices if it is not made un-mineable by mining the higher grade, lower cost portions, and this does make the problem greater than is indicated by this statement.

S.H.U. BOWIE: Thank you Mr. Nininger. Picking the "eyes" out of properties so that the total reserves cannot be mined economically is a problem that has to be borne in mind all the way through the business of recovering any kind of raw material from the ground.

A.G. DARNLEY: I wonder if we might consider showing the consequences of a delay, assuming perhaps three years before there is any substantial up-swing in exploration activity, on the required rate of discovery. I think one of the problems we are up against is in producing arguments which will persuade financial administrators in companies and governments to provide funds for systematic work now. I am afraid non-technical people tend to say "what was the rate of discovery when the Elliot Lake area was discovered? X hundreds of thousands of tons were added to the reserves in the matter of 12 months, so surely when the need arises we can do this again". I think this is the sort of opinion we must counteract.

J. BRINCK: At the end of this Panel I think we may come to a problem because we may have to advise the Agency what to do in the field of exploration. If we are talking about one million tons reserve at this moment, this represents many years of demand at the present level, certainly too much to really justify an intensive exploration program. I think there is a great danger here because we know the demands are growing and exploration should be done on a very continuous basis, so I think that the Panel should consider downgrading some of this reserve of one million tons and really try to talk about what reserves really are at current prices. Then you will see that there is really a problem for the future. I do not think you can make this credible on a reserve of nearly one million tons when you need only two million until the end of the century and if it takes only, say, ten years to find new reserves. If you look at the ENEA estimates of 1965 and 1966, I think we started out with about 450 000 tons, then we increased that with a lot of by-product material to about 600 000 or 700 000 tons, and now we are talking about one million tons and in these one million tons a lot of the by-product reserve does not even figure. So I think it is very difficult to justify a prospecting campaign on the basis of this type of reserve estimate.

S.H.U. BOWIE: Thank you for that comment, but I should like to make it clear that it is not the function of this Panel to re-examine the reserve figures in any more detail. This will be done by a joint IAEA/ENEA Panel in October this year.

J. CAMERON: Although I fully agree with you, I also think that the point Mr. Brinck has expressed is valid. One of the things that this Panel could very valuably do is to express the opinion that there is a problem and that these one million tons should be considered with reservations. They are not fully available, being limited or qualified by the real market price, the dependence on other metal production, on plant capacities and several other factors.

PANEL REPORT

Presently estimated reasonably assured resources at US $10 per pound or less are about one million metric tons of U_3O_8 (excluding the USSR, Eastern Europe and China). Against these reserves, the cumulative requirement through the year 2000 has been estimated at about 2.7 million metric tons.[1] An adequate additional reserve to assure the production base necessary to meet the large annual requirements in the later years might be of the order of 0.5 to one million metric tons, bringing the total reserve which needs to be developed to around 3.5 million tons. Of this there remains to be discovered some 2.5 million metric tons. The existence of resources, in addition to those reasonably assured, of one million tons has been postulated to occur "in unexplored extensions of known deposits or in undiscovered deposits in known uranium districts".[2] There is also an estimated potential of 1.4 million metric tons in reasonably assured and estimated additional resources in the $10-$15 per pound cost range. Thus, theoretically, the necessary uranium supply could be available at costs up to $15 per pound on the assumption that the approximately 1.6 million tons in the undiscovered "estimated additional" categories in both price ranges could, in fact, be discovered and brought into production on the schedule needed.

There are, however, a number of cautionary comments which should be made. The time period of 27 years is short. Moreover, the time of peak demand before breeder reactors begin to reduce requirements may be as much as 10 years earlier, i.e. about 1990, an extremely short period for such a major prospecting program. The lead time required after discovery to prove and bring into production new resources will further shorten the time available for exploration.

Apart from the limited reserves and production capability being developed by Government organizations to supply relatively small national nuclear power programs, the uranium needed in the future will be produced by commerical organizations. The supply and demand situation and the resulting market price will largely control the funds available and thus the aggressiveness of the exploration and development programs of these organizations.

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Unfortunately, uranium is presently selling at prices much lower than the lowest cost categories which have been used as a basis for the estimates of reserves and resources, owing to a short-term over-supply of uranium. Exploration, as a result, has been substantially reduced in the major producing countries. Furthermore, the reserves available at these lower market prices are much smaller than the currently quoted estimates. Although the price is expected to firm in the late 1970s, it is unlikely that it will reach $10 per pound until much later. Thus there will be no incentive to explore for $10-15 reserves; and such higher cost resources, to the extent that they are associated with lower-cost ores, may become unavailable for future mining owing to removal of the latter. Part of the ore in even lower-cost reserves will also be lost. For these reasons, and because of the short time period referred to, it would appear unrealistic to count on realizing the full quantity of the resources now estimated. A shortage thus seems likely to develop unless substantial discoveries beyond those now postulated are made.

The Panel has been asked to advise the Agency on what its policy should be in the light of the current situation and the very large future exploration requirements foreseen. The Agency obviously cannot directly influence the uranium market. The Panel suggest, however, that the Agency can do a number of things to affect positively the eventual outcome. It can

(a) Continue to assess the future demand and availability of resources to help evaluate the problem
(b) Continue to facilitate and, if feasible, increase the exchange of information on uranium geology and exploration technology
(c) Encourage and, where appropriate, support research programs in these areas
(d) Continue to provide technical advice and financial assistance to developing countries which have not been extensively explored but in which the opportunities for discovery of uranium appear favourable.

The Panel strongly recommends these actions in order to improve the opportunities for, and shorten the time required, for exploration success once the uranium market again encourages major increases in commerical exploration effort. Each year of reduced exploration increases substantially the later effort that will be required.

Finally, the Panel suggests that it would be extremely useful if the exchange of technical information and the assessment of supply and demand could be broadened to include those countries not now participating, in order to develop a truly world-wide picture and to enhance the technical base for future uranium exploration.

2. SURVEY OF PRESENT METHODS

SECRETARIAT REQUEST TO THE PANEL

One of the objectives of the Panel meeting was to make a survey of existing methods and techniques in uranium exploration and, where possible, to indicate the appropriate applications, advantages and limitations of each method, taking into account geological environment, topography, climate, temperature, etc.

The Panel was requested to provide a general report and if possible to summarize their views on each method under the subject headings of 1. Application (a) general (b) appropriate combination with other methods. 2. Advantages (a) geographic (b) geological (c) cost (d) other. 3. Limitations (a) geographic (b) geological (c) cost (d) other and 4. General Comment.

PANEL REPORT

A. GENERAL

Introduction

The fact that uranium undergoes radioactive decay makes it especially amenable to discovery and evaluation by methods based on the physical measurement of radioactivity. Alpha, beta or gamma radiation may be measured to detect one or more of the decay products of uranium. Gamma radiation is most useful because it has the greatest penetration range. Besides physical methods of measurement, the geochemical estimation of uranium and/or associated trace elements can provide a useful prospecting method. Before summarizing the available techniques, it must be emphasized that particular geographical and geological situations will often determine the most effective exploration technique. These factors must also be taken into account in data interpretation. The quantitative results provided by geophysical and geochemical techniques must be related to geology and must be reconciled with it. The most successful exploration programs are usually based on a judicious combination of methods; single techniques are rarely wholly effective on their own.

Geological base mapping

A geological base map of the proposed area is essential to any systematic mineral exploration program. If a map of a suitable standard does not exist, then it must be prepared either prior to or in conjunction with the preliminary uranium exploration work. Various airborne methods of exploration such as photography, including colour photography in many areas, and aeromagnetic surveys can be particularly valuable in accelerating and raising the standard of geological base mapping. Airborne gamma-ray and gamma spectrometry are good mapping tools, as is infrared imagery. Radar can be used to develop a base map under poor photo conditions.

Gross-count gamma radiation surveys

Gross-count gamma radiation surveys are made with geiger or scintillation counters which are hand-carried, carborne, airborne, lowered in a borehole, or trailed on a lake or sea floor. The major advantage possessed by geiger counters is their low cost. Geiger counters are relatively insensitive and generally are not suitable for preliminary exploration work except in special circumstances where low-cost instrumentation is a critical factor. In exploration work, geiger counters are used to evaluate ore grade concentrations.

Airborne gross-count radioactivity surveys provide relatively low-cost prospecting of large areas. Ground follow-up is essential. In many areas numerous anomalies unrelated to uranium deposits may require excessive ground work to evaluate them. In mountainous areas, a helicopter is essential to ensure reasonably complete ground coverage.

Carborne surveys are useful for prospecting in areas where the terrain is suitable for vehicles to traverse. These surveys can be combined with geological reconnaissance and thereby minimize overhead costs. However, as soon as the nature of the terrain starts to impose restrictions on choice of traverse line, then the survey becomes less thorough. For example, a carborne survey restricted to alluvium-filled valleys clearly could be misleading because it does not measure the radioactivity of the bedrock in the area.

Hand-carried counters form the basis of any detailed surface investigation and should be available to any field geologist carrying out investigations in areas where radioactive minerals may occur. If sufficient manpower is available, quite large surface areas can be systematically surveyed to compile maps of the radioactivity. Traversing on foot allows the most thorough search of an area and should be combined with grab sampling of interesting material. Usually, surface surveys on foot are restricted, because of the time required and cost factors, to anomalous areas which have been identified by one of the broader-range methods of survey. Useful accessories include differential face scanners and hole probes to permit quantitative measurements of outcrops and in shallow test holes.

Gamma spectrometer surveys

A gamma spectrometer is a more sophisticated and therefore larger and more expensive version of a scintillation counter. Its advantage is that it allows the discrimination of the three principle radioactive elements, potassium, uranium and thorium. In a total radiation survey the radiation from all three of these elements is summed together. Since only a small proportion of anomalous total radioactivity is due to uranium mineralization, it is clearly beneficial to be able to isolate those anomalies which are primarily caused by this element alone. This discriminating function of the equipment compensates for its greater cost, complexity and weight. Its most important application is in airborne equipment where there is no possibility of collecting specimen material for laboratory analysis. Ratios of the radioelements are often more diagnostic and more sensitive than total gamma measurements because they are affected less by geometry and unevaluated absorbers, and because variations in the ratios may indicate geochemical-geological environments.

Spectral data is less ambiguous and permits more complete and reliable interpretation of airborne data prior to selecting sites for ground investigation. Interpretation of spectrometer data is more difficult than gross count data and needs a good knowledge of the various elements in the decay scheme. High-sensitivity spectrometry, when combined with photogeology, can provide good geological-geochemical maps and data for initial evaluation of the favourability of areas.

Radon measurement in soil and subsoil

Radon, which is a radioactive decay product of uranium, is a noble gas and has a half-life of 3.8 d. Because of this it can diffuse or be transported some distance through fissures and unconsolidated material. Therefore, it can serve as a pointer to buried uranium which might not be identified by low-sensitivity total gamma radiation measurements. Radon (^{222}Rn) and thoron (^{220}Rn) are readily distinguished by their half-lives, and measurements are unaffected by potassium. Identification of the parent isotope is therefore possible. Disequilibrium between parent uranium and radium, and variation in emanation and porosity as well as mobility of radon introduces problems in interpretation. However, high sensitivity can be obtained with simple instruments, and radon measurements supplement total gamma surveys to delineate low-contrast "anomalies". Clearly the mobility of radon introduces problems in interpretation as well as advantages in detection.

Geochemical surveys

Stream or lake sediment surveys can be an efficient method in the search for uranium, especially where information is also sought about other elements of economic interest. Soil surveys may be used in arid areas or more generally where systematic detailed information is required to investigate an area of particular interest. As with other methods, the sampling and analytical procedures must be properly controlled to ensure that significant results are being obtained.

Water sampling for uranium and/or radon is a relatively inexpensive reconnaissance method. It can be applied to surface waters or to subsurface water in wells, etc. Especially in the case of well samples, invisible factors may influence the results and particular caution must be observed in making interpretations.

Geobotanical surveys

Geobotanical surveys normally only merit consideration as a last resort in view of the fact that the element distribution pattern is controlled not only by the soil distribution but also by the biological activity of the plant and its stage of growth.

Exploration drilling

Drilling constitutes a major part of most exploration programs but it is emphasized that in the present context it is drilling as a primary exploration tool and not as an evaluation tool which is being considered.

Drill holes provide access to vertical sections of rocks in concealed areas for lithologic, stratigraphic, mineralogical, geophysical and geochemical measurements. In many areas, drilling may be required in the early phases of a program to confirm regional geological projections and to obtain the subsurface geological information needed to assess the favourability of potential host rocks. In areas of extensive flat-lying sediments where there is reason to believe that a subsurface horizon may contain uranium, drilling is useful in early reconnaissance mapping as well as in the later stages of exploration.

Non-core drilling, combined with gamma-ray and electric logging or other in-hole geophysical measurements, supplemented by studies of cuttings from the hole, can provide most of the geological and assay data at a relatively low cost. Nuclear logging of holes previously drilled for other purposes, including cased wells, can provide valuable low-cost regional subsurface information. Rotary drilling and quantitative logging have proven particularly economic and effective for exploring sandstone-type deposits. Drilling is required to discover deeply buried deposits having no near-surface expression.

Techniques range from hand or power augers, through air- and mud-rotary, percussion, churn and plug drilling, to core drilling with diamond bits.

B. SUMMARY REPORT ON EACH PRINCIPAL METHOD

I. Geological mapping

1. Application

(a) General

Geological information on lithology and structure, mineral occurrences, topography, streams, roads, and other culture, land subdivisions and possibly ownership can be compiled and summarized on a small-scale (large-area) geological base map of a region or area. These are the factors needed (1) to select areas for preliminary evaluation, (2) to plan an effective program (determine appropriate methods and schedules) and (3) to estimate cost and budget.

Intermediate-scale base maps of project areas are needed (1) to compile and correlate local more-detailed geological information, (2) to record results of investigations and (3) to correlate survey measurements with geology for evaluation and interpretation. Finally, large-scale project summary maps are used to record detailed surface or subsurface geological features, traverse lines, samples and interpretation(s) of the relationships between geological, geophysical and geochemical data and between these parameters and clusters of uranium anomalies or the shape and intensity of anomalies. These correlations between uranium and geological-geochemical features (1) provide the basis for classifying the deposit, for predicting its possible magnitude and

economic significance and (2) are used to plan detailed exploration, to estimate grade and tons, and to evaluate the probable economic significance. In other words, these maps provide the technical and engineering support for decisions to abandon or continue exploration efforts and expenditures.

Geological mapping methods are essentially the same as used for exploration programs for other minerals and petroleum. Emphasis is placed on mapping geological environments which have proven favourable elsewhere.

(b) Appropriate combinations with other methods

The geological base map of appropriate scale is needed to effectively plan all other programs and to interpret and evaluate results of other studies. Conversely, geophysical and geochemical investigations support geological mapping. A good example is the strong synergistic yield of information obtained by combining sensitive airborne gamma-ray spectrometry with photogeological mapping of previously unmapped areas.

2. Advantages

(a) Geographical

Geological base maps can be used for logistical planning – siting project headquarters, field offices, estimating time and cost on the basis of size of areas, distances from supply centres, access and trafficability.

(b) Geological

The geological map permits classification of geological environments to identify areas containing geological features and characteristics similar to areas of proven favourability elsewhere. This permits evaluation by analogy and utilizes previous experience and experiences of others in the literature.

(c) Cost

Often geological maps are available and can be utilized or at most checked and refined at a very low cost per unit area. Photogeological mapping with only minor ground checking may provide an adequate preliminary map in many areas, again at low cost if photography is available.

(d) Other

Mapping can often be obtained from service contractors and does not require staffing to establish mapping capability.

3. Limitations

(a) Geographical

Undeveloped remote regions are not usually covered by adequate geological mapping. In many such areas it may be necessary to establish primary control stations to obtain high-level photography or radar imagery for establishing a planimetric base before adequate mapping can be undertaken. As a consequence, long lead-times can develop with large capital investments just to get started.

Geological mapping is limited to areas for which permission to operate has been obtained.

(b) Geological

The geological base map may be ineffective in areas where bedrock geology is mostly obscured by overburden, particularly in areas of complex geology where infrequent outcrops do not permit reliable mapping. Also, surface geology may not reflect favourable buried subsurface environments. Drilling and geophysical projects may be required to map significant subsurface geology.

(c) Cost

Investment of time and funds to obtain an adequate map may be prohibitive for small organizations or may not be justified as to priority in programs of small nations. Mapping and attendent costs may result in developing negative information — indications that the mapped area is not favourable. Therefore, preliminary geological reconnaissance and possibly rudimentary mapping may be desirable before initiating the program. Again this develops a long lead-time before adequate geological maps are completed and available to plan and guide the exploration program.

4. General comments

Geological mapping may be applied to developing many types of resources and therefore every effort should be made to establish co-operative mapping programs.

II. Ground surveys by portable GM and scintillation counters

1. Application

(a) General

GM portable survey meters are no longer used for general prospecting because of low sensitivity. GM meters are now more commonly used for grade control in underground and open-pit mines.

Portable scintillation (NaI) gross-count (total-count) ratemeters are the basic prospecting instrument. Applications include:

(1) Rapid and continuous monitoring of the relative radioactivity of rocks and soils in situ; it is the primary source of information on possible uranium concentration and is used for random traverses on foot and by vehicle when looking for anomalies, and to support geological mapping.
(2) Systematic surveys to map the radioactivity of rocks and soils and to locate low-intensity anomalies (less common in recent years).
(3) Qualitative testing of cuttings, cores, or other samples, and reconnaissance of old mines. When an accessory filter is used, the gamma-counter can provide quantitative equivalent uranium assays of outcrops, low-grade ore facies, etc.
(4) Portable scintillation counters are the primary instruments used to locate airborne survey anomalies on the ground.
(5) Portable scintillation counters, especially those with accessory recorders or remote alarm meters, can be used for carborne surveys at slow speed if more specialized instruments are not available.

(b) Appropriate combination with other methods

This primary general-purpose instrument is used to ground-check airborne surveys and provides the initial or supplemental radiometric data to guide most other ground survey methods such as radon, magnetics, I. P. etc. Portable scintillation counters are used to monitor cuttings and cores from drilling (largely replaced by logging in recent years). It is commonly used to qualitatively check specimens and samples from the field or museum collections.

2. Advantages

(a) Geographical

These compact, lightweight, simple instruments function over a broad range of temperature and can be used in most geographical environments.

(b) Geological

Gamma activity of lithologic units is often characteristic and can be used for mapping with sensitive portable scintillation counters. It readily indicates minor concentrations of radioactive minerals.

(c) Cost

The unit cost for equipment is low; the cost of an adequate GM portable counter ranges from about \$250 to \$550 and reliable field scintillation counters cost about \$900 to \$1200. Survey costs depend

on personnel cost, trafficability, percentage of area investigated and type of output or required records, e.g. simple search for anomalies or systematic mapping with geological observations, etc. Small areas can be investigated with a minimum investment in equipment and by mostly nonprofessional staff. On the average, a one- or two-man party can investigate about $\frac{1}{4}$ - 1 km^2/d at a cost of perhaps \$50/km^2.

(d) Other

Values are continuously displayed to guide the operator in the field, high reliability of functioning, simple data. Responds to gamma sources several metres distant (air-path) and monitors a large sample volume; rapid response directs operator to point of maximum activity.

3. Limitations

(a) Geographical

Temperature range: -40° to +50°C, gamma measurements over swamp or ice impractical.

(b) Geological

Gross count will not permit identification of source isotope. Penetration of gamma rays through rock and soil is limited to perhaps 10-20 cm; instruments respond to the near-surface material only.

(c) Cost

Time required to survey large areas in detail may be prohibitive. Close-spaced grid surveys to obtain "total coverage" of large areas is impractical and is better accomplished by airborne methods. Radiometric gridding is generally too costly in time and labor to be used as the reconnaissance search method and should be limited to favorable locations.

(d) Other

GM detectors are too insensitive for regional prospecting or mapping; most commercially available scintillation counters have insufficient rate capacity for work with commercial-grade ore and can be damaged by severe mechanical shock. A differential scanner-type detector must be employed to standardize the sample geometry and to eliminate the influence of adjacent materials ("background") if quantitative in-situ "assays" are required. Disequilibrium, which is common in the near-surface environment, and variations in potassium or thorium content cannot be evaluated with GM or most portable scintillation counters.

III. Gross-count (total-count) carborne surveys

1. Application

(a) General

The method is used for a preliminary rapid reconnaissance for anomalous gamma activity which may occur along roads, tracks and in relatively open trafficable country and may be related to favourable areas and possible occurrences of uranium at or near the surface, and it is also used to support geological mapping.

(b) Appropriate combination with other methods

Portable gamma counters are needed for local ground search, mapping, and preliminary evaluation of anomalies; apparent "anomalies" should be tested with spectrometric techniques (either vehicular-mounted or portable instruments) and may be followed up with radon measurements, possibly in conjunction with electrical survey, grab sampling, reconnaissance drilling and logging, or trenching. The method may be used as a preliminary reconnaissance survey of very large areas with a skeleton road network to select areas for more costly airborne or geochemical surveys.

2. Advantages

(a) Geographical

Moderate-sized areas, with appropriate terrain, can be investigated rapidly; surveys can be controlled with rudimentary road maps.

(b) Geological

Variation in soil and rock types or outcrops are commonly distinguished on continuous records. "Normal" background, typical of a lithologic unit, may be rapidly determined. Facies changes may be indicated. Data is immediately available and can guide additional field investigations.

(c) Cost

The cost of special equipment but without vehicle ranges from \$4000 to \$8000 depending on sensitivity and type of recording system. Good-quality general-purpose "portable" scintillation counters and recorders, costing less than \$2000, may provide adequate though limited survey capability under favourable conditions. Cost of survey depends on wage scale and trafficability: 50-300 km/d at costs of up to \$100-\$200 (two men). Areas too small for economical airborne surveys may warrant rapid reconnaissance with carborne equipment.

(d) Other

Traverse speeds of 10-30 km/h are not uncommon, much greater than foot or horse traversing. The detector can be elevated (foliage permitting) to broaden coverage (zone of influence). A permanent analogue or digital record can be obtained for later study and correlation to geology. Observations can be recorded on tape and related to the gamma record; this may permit one-man operations.

3. Limitations

(a) Geographical

Limited by vehicle trafficability in many rough, brush, or forested areas. Temperature range for optimum operation: -20° to +45°C. Rain or snow hampers measurements and trafficability.

(b) Geological

Potential host rocks or structures should be at or near the surface — buried occurrences will have little to no expression. In the gross-count mode it is impossible to identify the anomalous isotope (U, Th or K). Generally the shape and extent of the anomaly is not indicated by the carborne record.

(c) Cost

Expenditure for special equipment is not warranted unless several thousand line kilometers are to be surveyed.

(d) Other

Many "apparent" anomalies are generated because the gamma intensity at the detector depends on many parameters, e. g. geometry, radioelement concentration, intervening absorbers, etc., and careful concurrent observations, as well as local field checks, are required to evaluate the survey records; variations in parameters other than concentration of radioelements generally prevent quantitative analysis of the records. Variation in road materials dominate measurements along improved roads. The carborne instrument responds to a larger sample than when used on foot but the area of influence is very much smaller than an airborne configuration; coverage is poor unless many closely spaced traverses are possible.

4. General comment

Although not extensively used in areas of flat-lying sedimentary rocks where other methods may be more effective, it has been used with positive results in many countries.

IV. Gross-count (total-count) airborne surveys

1. Application

(a) General

The method is used for the rapid reconnaissance of relatively large areas to discover anomalies which may be related to deposits and to map relative gamma activity which may be related to geology.

(b) Appropriate combination with other methods

Magnetic (field) and electromagnetic measurements, which can be recorded simultaneously with the gamma activity, provide supplemental data to reduce ambiguities in analysis; these data are especially valuable when surveying areas of complex structure in crystalline rock environments; gamma surveys should be integrated with geological mapping.

2. Advantages

(a) Geographical

Large inaccessible areas, particularly in remote regions, can be rapidly surveyed by a small staff or contractor. Flat areas are most suitable for airborne survey but application in most mountainous areas is usually possible.

(b) Geological

Patterns of natural gamma intensity reflect variations of surface geology and are particularly valuable for unmapped areas, to supply refining detail to reconnaissance maps and to identify points of geological interest.

(c) Cost

Cost of data acquisition depends on local conditions including topography, remoteness and size of the area, and availability of adequate mosaics and base maps. These may range from about \$3 to \$6 per line km. Costs of data analysis depend on degree of sophistication; cursory identification of apparent major anomalies is fast and cheap compared with in-depth evaluation of data to identify subtle anomalies and make geological analyses. These costs may range from \$2-\$20/km^2. Ground checking is additional and commonly exceeds costs of flying and data analysis. Total costs of a modest-sized survey are significantly less than for developing the same regional data by ground methods, especially in remote areas of poor trafficability, and information is developed much more rapidly. Gross-count (total-count) systems are much less costly than adequate spectrometric systems.

(d) Other

Airborne gamma measurements provide continuous representative sampling of broad areas. Data is amenable to statistical analysis. Surveys can be provided by service contractors and may be performed separately or in parallel with other exploration projects.

3. Limitations

(a) Geographical

Areas of high relief may not be amenable to flying with low-cost fixed-wing aircraft; high altitude may require special aircraft; remote areas greatly increase costs if helicopters are required; terrain may dictate a flight line pattern which is not optimum (contour flying or short line fill-in of spots); climatic and weather conditions limit periods of successful or economic operations, e. g., snow, flooding, dust, turbulence, cloud, inversions, etc. In densely forested areas, the impossibility of distinguishing visually between formational changes and potential deposits makes interpretation difficult.

(b) Geological

Areas covered by alluvium, glacial deposits, ice, peat, etc. effectively obscure the gamma signal from bedrock. Broad areas of undisturbed sediments or volcanics can be "mapped" but almost always obscure radiometric evidence of buried deposits. Geological units can be mapped only when they provide significant contrasts in total gamma intensity; e. g. two compositionally similar units of greatly different age or texture cannot be distinguished and small inherent differences in radioactivity are commonly obscured by variation in surface absorbers such as soil moisture, vegetation and per cent of outcrop.

(c) Cost

Capital cost of the instrumentation for gamma measurements and recommended supporting equipment such as altimeter, tracking camera or doppler, but not including the aircraft, may range from $8000-$15 000 (more for doppler navigation). It is therefore not economical to develop a system for a single small project. Alternatively, a service contractor may be more economical for single projects, but small projects are more costly per km^2 than large projects. Costs of ground checking to complete the evaluation of gross-count surveys commonly exceed the cost of data acquisition because of ambiguities in data and the high proportion of "apparent" anomalies which warrant field investigation.

(d) Other

When ground clearance is sufficient to obtain coverage and safety (100 m or more), the method does not efficiently identify local

"point source" anomalies which are averaged into the large sample. The gross-count (total-count) mode cannot distinguish uranium from thorium, potassium, or combined anomalies. Also, the intensity of gamma activity (the count rate) is influenced by surface absorbers such as soil, moisture, vegetation, etc., and by geometric variations caused by topography. Variation in atmospheric radon and gamma-emitting daughters can produce apparent anomalies not related to ground radioactivity.

4. General comments

The method has been used successfully in many regions of the world to evaluate favourable areas and to locate deposits. It is most applicable to rapid reconnaissance in the early stages of exploration and to moderate-sized areas, preferably areas containing relatively uncomplicated and mapped geology. Projects should be designed to sample and evaluate broad areas; direct discovery of deposits is desirable but not the only or even the primary immediate objective.

V. Portable and carborne gamma-ray spectrometer surveys

1. Application

(a) General

The method is used for two types of programs requiring independent measurements of U, Th and K. These are:

(1) Direct prospecting, in which the spectrometer is used in the gross-count mode, to discover anomalies associated with deposits but using the spectral capability to distinguish between anomalies caused by concentrations of U, Th or K.
(2) Geochemical-geological investigations, including mapping, to evaluate favourability, e.g., relative concentrations and ratios in rock units, zones of alteration and variations associated with structures.

(b) Appropriate combination with other methods

It is used to evaluate anomalies discovered by other methods such as airborne gamma and magnetic surveys; to support general geological mapping projects, and to supplement geochemical surveys of rocks and soils. It also works well in conjunction with radon and magnetic susceptibility.

2. Advantages

(a) Geographical

Portable instruments can be used in most geographical environments; rapid broad coverage is possible in areas with vehicular accessibility. The method provides good resolution of point or

line sources and develops information about the form of the anomaly. Ratio values, based on measurement of selected high-energy gamma-ray photopeaks, are affected less by geometry and absorbers than are measurements of intensity (relative concentration); this is a major advantage over gross-count methods but requires adequate detector sensitivity.

(b) Geological

The relative equivalent concentrations of U, Th and K can be determined in the field and compared with field relationships, e.g. lithologic or structural features. Commonly, variations in U, Th and K or ratios of these reflect geological units or environment history.

(c) Cost

A trade-off of time-for-measurement for relatively low-cost equipment makes these spectrometers suitable for small projects which do not warrant surveys using more sophisticated high-cost airborne systems. Cost per measurement is commonly less than collecting samples followed by laboratory analysis. Equipment costs range from about US $2000 to $10 000; operating costs range from $1 per single location measurement to about $5-$10/km of traverse with the more sophisticated carborne units.

(d) Other

Volume of "sample" influencing the field spectrometer is larger and presumably more representative than most samples collected for analysis in the laboratory. The "large sample" permits relatively short measurement time compared with laboratory spectrometers. Values are immediately available to guide field work.

3. Limitations

(a) Geographical

Operation of the equipment is limited by ambient temperatures (-20°C to +40°C) and carborne equipment is restricted to trafficability. The more sophisticated equipment is difficult to maintain in remote areas. Variations in topography and absorbers greatly influence gamma-ray intensity (relative concentration).

(b) Geological

Cover materials such as alluvium, swamp and ice absorb the diagnostic gamma rays from bedrock. Deposits at depth do not influence the detector directly — only the near-surface materials are measured.

(c) Cost

Capital cost of equipment is generally several times greater than for gross-count equipment; maintenance costs are greater and there is usually more "down time". Spectral measurements require more time than gross count. Therefore, total costs for the spectral surveys are commonly 5 to 10 times greater than simple gross-count gamma surveys. (This is not usually a serious limitation if the value of additional spectral information is considered.)

(d) Other

Instruments require frequent calibration; measurements are qualitative, can seldom be related to absolute concentrations and disequilibrium may introduce errors.

In the case of carborne survey, characteristic radiation is partly shielded by the vehicle body; the magnitude of this effect depends on detector placement. This type of survey should not be attempted unless a large volume of crystal can be provided.

4. General comments

(a) Optimum results generally require a good understanding of the physical and geochemical parameters of the instrumentation and methods.

(b) More information can be obtained from spectral measurements but may not always be required by the exploration program – judgement is required in adopting the method.

VI. Airborne gamma-ray spectrometer surveys

1. Application

(a) General

In practice two rather distinct approaches to airborne gamma-ray spectrometry have been developed to meet somewhat different objectives. One method uses a combination of gross-count and a minimal spectral capability to achieve limited objectives. The other utilizes a high-sensitivity spectrometric capability to provide a sophisticated multi-parameter geochemical-statistical evaluation. The minimum system depends on gross-count for rapid regional search for anomalies and rudimentary geological mapping; spectral measurement of anomalies may identify the primary isotope, U, Th or K. The high-sensitivity spectral method is used for regional and area geochemical-geological mapping and to detect and map variations in lithology and anomalous

radioelement ratios. Continuous ratio mapping is used to discover subtle anomalies often not indicated by gamma intensity alone. Sensitive spectrometry is most efficiently used to evaluate favourability of broad areas and for preliminary geological mapping.

(b) Appropriate combination with other methods

Best combined with photogeology and statistical evaluation. Magnetic surveys can be made simultaneously; this combination is recommended for areas of structurally complex crystalline rocks.

2. Advantages

(a) Geographical

Can evaluate broad remote areas having poor ground access and trafficability. Does not intrude on landowners or environment.

(b) Geological

Capability to distinguish between major radioelements U, Th, and K. Broad "sample" provides good average values. Ratios obtained with the sensitive systems are less influenced by absorbers (soil, moisture, vegetation, etc.) and variations in geometry and are often more diagnostic of deposits than intensity measurements. Provides geochemical data to evaluate anomalies, geological environments, alteration, and, in many cases of in-situ soils or glacial overburden, may indicate bedrock types. Good spectral data greatly reduces the amount of ground checking required to evaluate favourability or to select significant anomalies or areas for supporting studies.

(c) Cost

Ranges from about \$10 to \$20 per line km, depending on type of data collected and degree of data processing, statistical evaluation, or output formats. Costs per unit area evaluated are often low because much high-cost ground checking is eliminated. These may range from US \$25/km^2 for initial reconnaissance mapping to US \$100/km^2 for detailed mapping, evaluation and selection of localities for additional exploration.

(d) Other

Data is applicable to the search for nonradioactive mineral deposits (general mineral deposits, e.g. Cu, Pb, etc., and possibly petroleum). Service may be contracted, thus reducing permanent or temporary staffing and eliminating capital investment and lead time to develop system and methods for small projects.

3. Limitations

(a) Geographical

Difficult to use over very high-relief terrain. Should not be used during periods of flood, or deep snow or ice cover. Flying is limited by weather and affected by atmospheric inversions.

(b) Geological

Swampy areas, dune sands or transported soils obscure bedrock data. Method responds to the surface materials. Count rate is influenced by unevaluated surface absorbers, geometry, and isotopes in the atmosphere; except for ratios, data tends to be qualitative.

(c) Cost

Capital costs for instrumentation, software, and time to develop working procedures are very large, especially for adequate high-sensitivity systems and methods, ($250 000 or more), and should not be initiated for small projects (for which service contractors should be used). Adequate service for high-sensitivity systems is very limited. Contract costs are high for small projects (less than 10 000 line km).

(d) Other

Operation and analysis of data requires highly skilled scientific and technical personnel. Unless an adequate system is used, data may be misleading and possibly less desirable than good gross-count surveys.

4. General comments

Adequate high-sensitivity systems with a strong program for data reduction and analysis constitute one of the best methods for identifying favourable areas and evaluating anomalies in a preliminary program. Many so-called spectral surveys are inadequate because of the survey system and because of insufficient data reduction and analysis. Users are cautioned either to obtain truly adequate spectral data or to use gross-count methods.

VII. Radon measurement surveys in soil and sub-soil

1. Application

(a) General

An emanometer or radon monitor measures the concentration of radon isotopes within the gases contained in soils, rocks and waters.

This instrument is used to search for uranium deposits by detection of anomalous concentrations of radon, thoron and their immediate decay products. The technique may distinguish between radon and thoron and provides a measurement which is independent of background gamma or beta radiation.

It can also be used to support geological mapping and interpret geological structure.

It works most satisfactorily when used to detect uranium deposits in rocks or structures covered by porous overburden.

The ultimate objective is to guide selection of the most favourable location for follow-up exploration such as drilling or trenching, particularly in soil-covered locations.

(b) Appropriate combination with other methods

The method is most effectively applied to areas which other methods and criteria, e.g. surface or airborne gamma surveys, geochemical surveys and favourable geology, have indicated as potentially promising.

2. Advantages

(a) Geographical

Several devices or instruments can be used and provide a choice adaptable to most geographical areas. Very portable or vehicle-mounted systems are available; low-cost manual sampling methods are available which utilize low labour costs in some areas or mechanized sampling can be used. Remoteness or vehicular accessibility influences the choice of equipment but is not limiting. Techniques are adaptable to many soils and climates.

(b) Geological

The technique, under favourable conditions, provides data in areas covered by soil and alluvium. Sensitivity is often sufficient to distinguish geological features, as well as anomalies.

(c) Cost

Capital investment in a system is moderate (\$2000-\$5000); relatively unskilled non-professional operators are satisfactory. Costs per measurement may range greatly from about \$0.50-\$10.00 and are competitive with other detailed surveys of small areas.

(d) Other

The method is very sensitive and commonly provides more detail and greater contrasts than other simple radiometric methods.

The method is not influenced by variations in potassium, and relative uranium and thorium concentrations can be indicated by decay rate measurements requiring only a slight increase in time and effort.

3. Limitations

(a) Geographical

Portable instruments or films have no geographical limitations; vehicle-mounted systems require access which may be limited by intensive agriculture or rugged terrain. Weather and climate are restrictive, e.g. swampy or frozen ground is unsuitable.

(b) Geological

Most radon methods are predicated on sampling soil gas, and therefore the soil must be sufficiently well-developed to provide a porous collection zone which is relatively isolated from the atmosphere. Migration of radon is very limited unless transported by atmospheric pumping or rapid groundwater flow. Depth of investigation is therefore very limited and radon cannot signal a deeply buried deposit unless long-lived parent isotopes have migrated to the sample site. Variations in concentration of radon are influenced by many parameters and moderate variations are often difficult to interpret.

(c) Cost

Cost of instrumentation is 2 to 5 times more than a good scintillation counter; cost of labour to obtain the sample is much greater than for a total-gamma measurement. Generally, the technique is not economically competitive with gamma surveying as the first phase of a project except under special conditions.

(d) Other

A number of factors influence the values measured and many apparent anomalies are not related to ore-grade uranium deposits. A good geochemical-geological model is necessary to evaluate all but the few very strong anomalies. Supporting sampling is often needed to resolve interpretation. The effect of changing weather conditions (speed of wind, barometric pressure, rain, snow, etc.) affects the reproducibility of values measured from one time to another.

4. General comments

The method has proven very successful under favourable conditions and very unsuccessful or at least not the optimum method under other conditions. The several techniques should be tested in each area prior to initiating a large project or relying totally on radon data to guide an

exploration program. Best results have been obtained where a few to tens of meters of soil cover mineralized sub-outcrops or fracture-vein systems. Only under special geological-geochemical conditions will near-surface concentrations of radon indirectly reflect the proximity of deeply buried flat-lying tabular deposits.

Recommended method in areas of crystalline rocks with autochthonous overburden development; very sensitive from point of view of area detection.

VIII. Radon measurement surveys in water

1. Application

(a) General

The measurement of radon in streams, lakes and springs may indicate favourable regions for uranium prospecting. It can be used to measure and determine radioelement migration. It has a general application in reconnaissance uranium prospection.

(b) Appropriate combination with other methods

It can be used alone as a preliminary reconnaissance method or as a follow-up to airborne and other types of surveys. Uranium can be determined analytically in the same sample.

2. Advantages

(a) Geographical

Rivers, streams, springs and lakes which are accessible can be surveyed.

(b) Geological

Provides a quick general knowledge of the radioactivity of an area and can strongly outline abnormally uraniferous rocks, e.g. granites, and is thus useful as an adjunct to basic geological mapping.

(c) Cost

Equipment costs \$4000-\$5000. A field camp laboratory can determine up to 150 samples per day (2 men).

(d) Other

Only ^{222}Rn is determined. The only primary source of this gas is ^{238}U.

3. Limitations

(a) Geographical

Use is confined to areas where adequate surface waters are available for sampling.

(b) Geological

Detailed interpretations require a knowledge of the groundwater hydrology of the area.

(c) Cost

Sampling costs may be relatively high in inaccessible areas.

(d) Other

Detailed interpretations of results may be difficult. Sampling should be carried out as much as possible in the same season. Results from different media (lake water, stream water, springs or groundwater) must not be mixed.

4. General comments

This method is applicable as a broad-scale reconnaissance method only. No attempt should be made to use it as a detailed method.

IX. Geochemical surveys (stream or lake sediment)

1. Application

(a) General

Stream sediment samples are used for preliminary reconnaissance of large areas.

(b) Appropriate combination with other methods

Stream sediment methods benefit from good geological and topographical maps or photo-geological control to select sample points and especially to evaluate data in a geological context. Follow-up with radiometric or other geophysical methods is common before drilling.

2. Advantages

(a) Geographical

Large areas in many parts of the world are suitable for one of these methods.

(b) Geological

Multi-element surveys may provide information on regional geochemistry which is needed to evaluate the favourability of the general environment; data can support geological mapping, particularly for covered areas with few exposures of bedrock.

(c) Cost

Sampling over a broad area can be accomplished by a small staff without expensive equipment. Assuming available laboratory capability, large areas can be surveyed at a low cost per km^2 prior to selecting the most promising localities for additional work.

(d) Other

Sampling program can be applied to exploration of other types of resources (other metals in particular). Field analyses are possible for some elements and can be used to guide work in the field.

3. Limitations

(a) Geographical

Very remote and undeveloped areas increase the cost of sampling and transporting samples to the laboratory. Some analyses can be obtained in the field. Good drainage patterns are advisable for stream sediment sampling; projects should be confined to drainages having similar gradients and maturity. Industry may generate artifact contamination.

(b) Geological

Anomalies may be localized in overburden and not related to local bedrock occurrences.

(c) Cost

Cost per sample, for either a field or laboratory multielement analysis, is generally greater than a radiometric determination. Equipment for an analytical laboratory might cost about US $10 000 and would require a large continuing input of samples to justify the expenditure. Value of the information must be balanced against cost of other possible methods.

(d) Other

Unless samples are analysed in the field, the delay in obtaining laboratory results precludes using them to guide sampling in progress.

4. General comments

Field processing of the samples may be desirable. This may include blending and splitting large samples for shipment to a laboratory, qualitative to semi-quantitative analysis using portable test kits or mobile field laboratories, or a combination of these. Stream sediment samples generally are more representative of broad areas, are lower in concentration, and have a lower variance than soil samples. Greater sensitivity and precision may be required for sediment samples. Airborne gamma surveys provide more rapid and broader "sample" coverage but do not yield information on related trace elements.

X. Geochemical surveys (soil)

1. Application

(a) General

The method is most appropriately used to make detailed surveys of small areas. In some tropical areas it may serve as a semi-reconnaissance method.

(b) Appropriate combination with other methods

May follow or replace reconnaissance airborne or carborne scintillation surveys. May be usefully combined with soil-gas radon surveys and detailed scintillation surveys.

2. Advantages

(a) Geographical

A rapid, sensitive method of locating drill targets within small areas.

(b) Geological

It can locate favourable structures and/or formations even when buried. Local geochemical studies of soil samples may be used to test radiometric anomalies.

(c) Cost

Analytical cost per sample is the same as for stream sediment samples. Labour costs are less because of the greater sample density.

(d) Other

Several elements associated with expected uranium mineralization may be determined on the same sample.

3. Limitations

(a) Geographical

The method depends on the type and depth of overburden and other factors of the physical environment.

(b) Geological

Sample density must be designed to suit the size of the target expected. Transported glacial overburden will not offer representative samples of underlying formations. Variance of small soil samples may be large and yield "apparent" variations which are misleading. Soil samples may represent a very local population.

(c) Cost

The method depends on large numbers of relatively low-cost analyses. These may not always be available. Equipment for an analytical laboratory might cost US $10 000 and would require a large continuing input of samples to justify its cost.

(d) Other

May not be applicable in areas where soil development is not suitable.

4. General comments

This is an effective detailed technique which should be particularly considered in areas of residual soil cover. More soil samples than sediment samples may be needed to make a representative or reliable evaluation.

XI. Hydrogeochemical surveys

1. Application

(a) General

Water sampling, whether applied to lakes, streams, springs, or wells, is a preliminary reconnaissance method used to identify possibly favourable areas warranting additional investigations with other methods. It is most valuable in areas with few outcrops, thick overburden or flat-lying buried host units, and in areas of moderate to deep weathering.

(b) Appropriate combination with other methods

Hydrogeochemistry should be combined with radiometric methods. Local anomalies from wells or springs may warrant preliminary

test drilling and logging to determine the probable cause and to derive other information needed to evaluate the favourability of the area and, if possible, its extent.

2. Advantages

(a) Geographical

Lake and stream sampling may be useful in areas having a high ratio of water to land, e. g. , Canadian Shield, and in areas with well-developed, closely spaced perennial drainage patterns which also usually coincide with heavy vegetation and soil cover.

(b) Geological

Chemical composition of waters tend to reflect local geochemistry and geology. Water samples generally exhibit a very low variance and constitute a reliable (repeatable) sample. Spring and well waters are influenced by subsurface geochemistry as well as by surface materials and, under favourable hydrological conditions, may be sensitive to large adjacent volumes of rock. Uranium tends to be soluble in the near-surface environment and is available to meteoric water.

(c) Cost

A large area may be amenable to testing with a few samples, hence sampling costs per unit area may be low. Analytical costs of water samples tend to be less (and less difficult to perform) than soil and rock analyses.

3. Limitations

(a) Geographical

Adequacy of sample coverage is dependent on the density and pattern of water sources. Seasonal and temporary variations in flow may influence values and limit sampling schedules.

(b) Geological

Above-average concentration of uranium in waters may not be indicative of uranium deposits. A number of factors such as dissolved or suspended inorganic and organic matter greatly influences the concentration of uranium in the sample. Broad rock-level sources can also furnish sufficient uranium to develop "anomalous" concentrations in the water. Concentration levels in waters tend to be several orders of magnitude less than in rocks and soils and require special sensitive analytical techniques.

(c) Cost

Cost per sample may be excessive if only a few samples are occasionally analysed. Supporting analyses to characterize the water may increase costs to \$10-\$30 per sample (about \$5 per ion). Adequate information may be developed by less costly methods.

(d) Other

A project should be designed, directed, and results interpreted by an experienced geochemist cognizant of the requirements and limitations of the method. Qualified personnel are difficult to locate, especially someone also familiar with uranium geology.

4. General comments

Hydrogeochemical surveys are generally considered as contributing potentially useful data during the reconnaissance phase of programs, by suggesting possible favourable areas warranting more intensive exploration efforts. Total reliance on hydrogeochemistry is imprudent – anomalies are only one of many favourability factors and do not in themselves identify deposits or even reliably indicate areas containing economic deposits. Conversely, deposits do not always generate extensive water anomalies. In spite of its limitations, experience has proven hydrogeochemistry can contribute to programs under favourable conditions and is worthy of consideration as part of many programs.

XII. Geobotanical surveys

1. Application

(a) General

Used only in specific types of terrain with suitable vegetation.

(b) Appropriate combination with other methods

Used in combination with ground geological mapping.

2. Advantages

(a) Geographical

Might be effective in areas of thick overburden.

(b) Geological

Very few advantages.

(c) Cost

No advantage over other methods.

(d) Other

No general advantages are seen. The method could only have advantages in very unusual and specific situations.

3. Limitations

(a) Geographical

It is not possible to use the method over very large areas.

(b) Geological

Element distribution pattern is controlled not only by the soil distribution, but also by the biological activity of the plant and its stage of growth.

(c) Cost

Sampling and analytical costs are high. Highly trained samplers are required.

(d) Other

Interpretation can be ambiguous. Extensive research may first be required to discover whether the method is suitable to any particular area.

4. General comments

Has very limited application to specific problems and cannot be used as a substitute for other exploration methods.

XIII. Other geophysical methods (non-radiometric)

1. Application

(a) General

Airborne geophysical techniques such as magnetics, EM, RF and infrared sensing may be used to support early reconnaissance and mapping of broad unassessed areas. These methods do not measure uranium directly but develop geological information and are most valuable over structurally complex areas, where

outcrops are sparse, and areas where the potentially favourable structures or host rocks are covered by younger rocks and overburden.

Surface methods, in addition, may include: gravimetric, magnetic susceptibility, electrical (resistivity, SP, IP) and seismic techniques. Surface measurements are generally limited to detailed investigations of small areas which have been identified as favourable by other work (e.g. airborne geophysics, geochemistry, etc.). The techniques are used to develop subsurface geological information and are most often used in areas of thick overburden or complex structure.

Selection of the method or of the combination of techniques should be based on local geological and survey conditions.

(b) Appropriate combination with other methods

Geophysical methods should nearly always be used in combination with and to support other exploration methods.

Airborne magnetic and RF surveys can be made concurrently with airborne gross-count or spectrometric gamma-ray surveys. The combined data often greatly improves the total interpretation and permits a more complete and sophisticated evaluation of the geology, particularly for areas with limited geological mapping. Results should be reconciled with available geological maps and photogeological interpretation should be integrated with the geophysical results.

Surface geophysical methods should be selected to solve specific geological problems, commonly subsurface problems. Data should be correlated with radiometric and geochemical surveys and interpretations tested or supplemented by drilling.

2. Advantages

(a) Geographical

Airborne methods are only slightly limited by geography — air strips in reasonable proximity, local artifact problems with power lines, buried pipes, etc., or high topographic relief.

(b) Geological

Depth of measurement is significantly greater than with radiometric or most geochemical methods, and generally valid data can be obtained through a moderate thickness of overburden. Many of the surface and airborne methods respond to a large and hence statistically significant sample volume. These methods could

be very suitable where the uranium mineralization sought has other known associates, e.g. sulphides. In this case, better localization might be obtained than with "conventional" uranium techniques.

(c) Cost

Geophysical methods provide subsurface information without or with only limited drilling; therefore, in areas of high-cost drilling, the geophysically derived data may be less costly. Geophysics may be used to trace deep features between holes or outcrops and to search for geological features which can be investigated with a few well-directed drill holes.

(d) Other

Classical geophysical surveys can be obtained from a number of service companies, thus eliminating the need for capital investment for equipment or for maintaining specialized staff.

3. Limitations

(a) Geographical

Surface methods require reasonable access to be cost competitive, and field work may be hampered by severe weather conditions.

(b) Geological

None of the "classical" methods provides direct detection of uranium, and responds only to possible related physical parameters of lithology, structure or associated minerals. Local conditions may not be suitable or targets may not be amenable to various methods; e.g. resistivity methods, particularly in arid regions, may have a limited depth capability or there may be insufficient contrast to obtain significant response.

Many methods provide ambiguous data unless "calibrated" or tested by some drilling.

(c) Cost

In many cases the classical geophysical methods are neither cost-competitive with other methods nor are the data provided worth the cost, e.g. shallow seismic measurements can outline paleo stream channels but may cost more than low-cost drilling which can in addition test for uranium.

Good equipment is expensive and an experienced professional staff is required. Therefore, cost of initiating single small projects may be prohibitive.

(d) Other

Most of the limitations are those imposed by the physics of the measurement and depend on local conditions and are not generally applicable, e.g. IP has successfully outlined some known sandstone-type deposits and has failed to indicate others in apparently similar settings.

4. General comments

Except for airborne methods, geophysical surveys are best employed to detail subsurface geology in areas of high-cost drilling or to solve specific geological problems, and have not been employed for general exploration.

XIV. Exploration drilling

1. Application

(a) General

It is emphasized that it is drilling as an exploration tool only and not primarily as an evaluation tool which is being considered. This is applicable mainly to sandstone-type deposits in certain specific types of geological environment. It is a method of investigation at depth where there may be no radiometric expression at surface, but where the geological indications are favourable.

(b) Appropriate combination with other methods

It must be combined with geological mapping, and radon surveys may be of assistance in defining target areas. It is usually subsequent to these and other methods.

2. Advantages

(a) Geographical

None.

(b) Geological

Core or cuttings are available for lithologic and mineralogic study and/or assay. Drill holes are available for radiometric and electric logging and water table determination.

(c) Cost

May preclude having to use other exploration techniques in easily accessible and appropriate areas and may provide more complete and accurate information.

(d) Other

Relatively rapid method of evaluating an area.

3. Limitations

(a) Geographical

Mountainous terrain and rugged topography may restrict sustained drilling operations.

(b) Geological

Results are restricted to drill hole geological situation. The drill hole is a very small sample and allows extrapolation only where exceptionally good lithologic uniformity exists.

(c) Cost

Up to the first 1000 ft, rotary non-core drilling may have an average cost of upwards from $1.00/ft in sandstone formations. A minimum total budget required to provide adequate information may be substantial.

(d) Other

As an exploration tool its application is limited to certain specific geological conditions and to organizations with substantial financial resources.

4. General comments

It may be the only method which can be used in areas with allochthonous overburden, in which case the relatively high cost must be supported.

C. DIAGRAMMATIC SUMMARY OF EXPLORATION METHODS AND PROGRAMS

The Panel wished to emphasize their view that the most successful exploration programs are usually based on a judicious combination of methods which take into account particular geographical and geological situations. To illustrate this view, Figs. 1-4 indicate diagrammatically the principal choice of methods in any exploration program. Geological input is required at all stages.

Clearly, every method has its place and these summaries and diagrams attempt to indicate the distinction which should be made between the various techniques and how they should be used in the different stages or phases of exploration, as well as the requirements and approximate cost of each technique in each of those phases.

The papers presented in the first part of this volume provide examples and case histories of the application of each of the techniques summarized in this report.

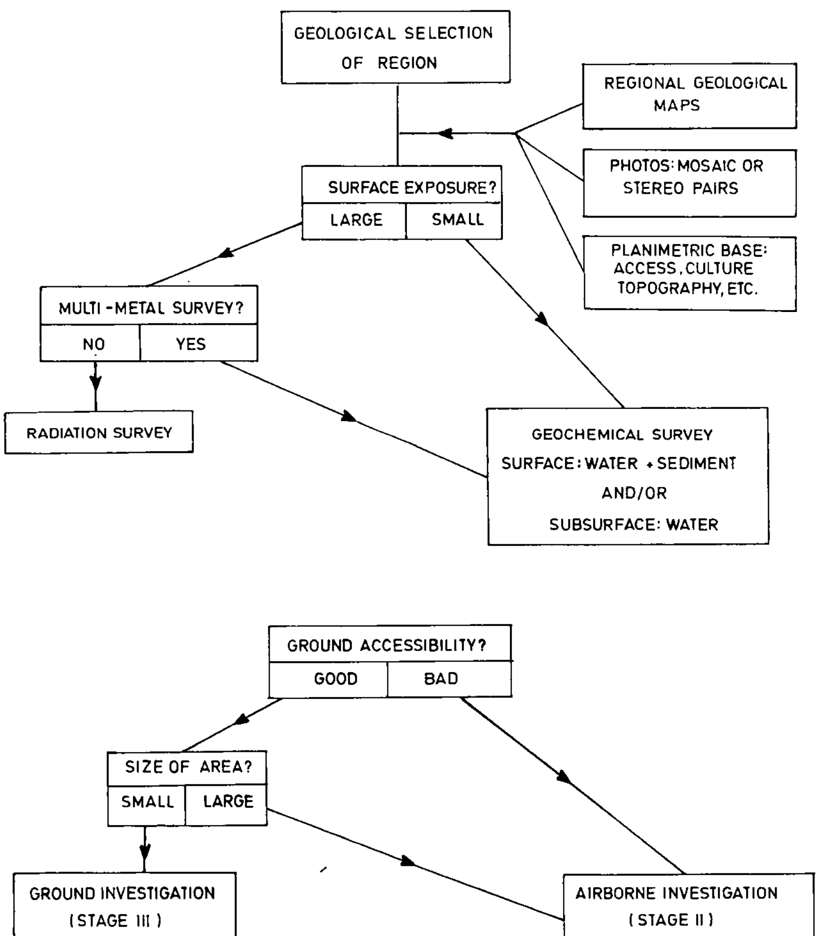
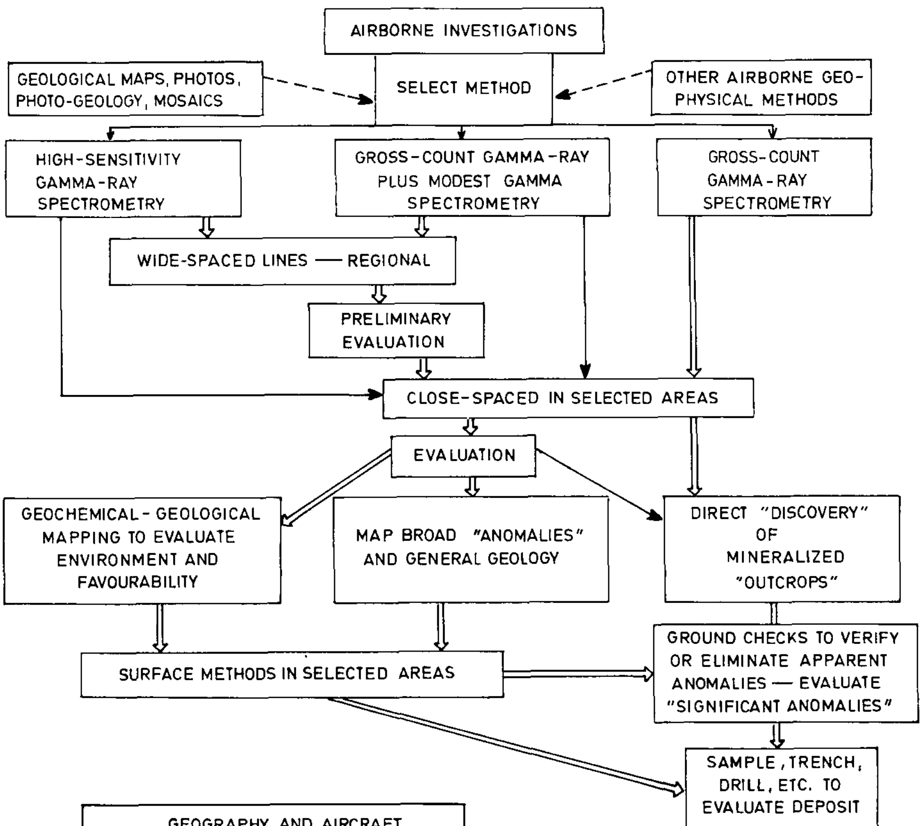


FIG. 1. Stage I: Preliminary decision-making.



GEOGRAPHY AND AIRCRAFT		
RELIEF	SIZE OF AREA	
	SMALL	LARGE
LOW	FIXED-WING LIGHT	FIXED-WING HEAVY
MODERATE	STOL	
HIGH	HELICOPTER	STOL

FIG. 2. Stage IIa: Progressive reduction of search areas based on radiometric surveys. Method depends on the primary objective of the survey.

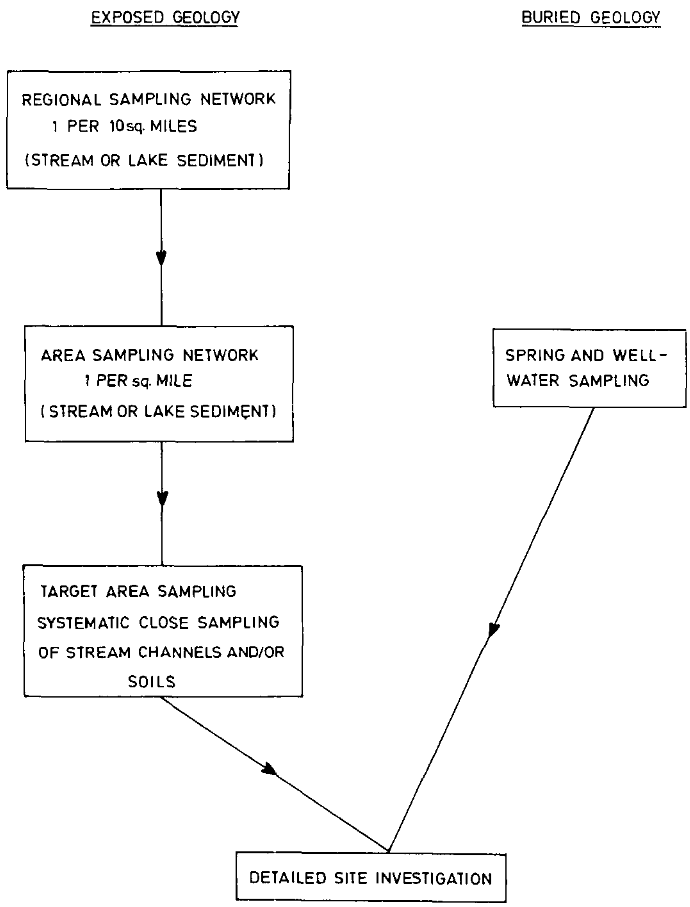


FIG. 3. Stage IIb: Geochemical multi-element approach.

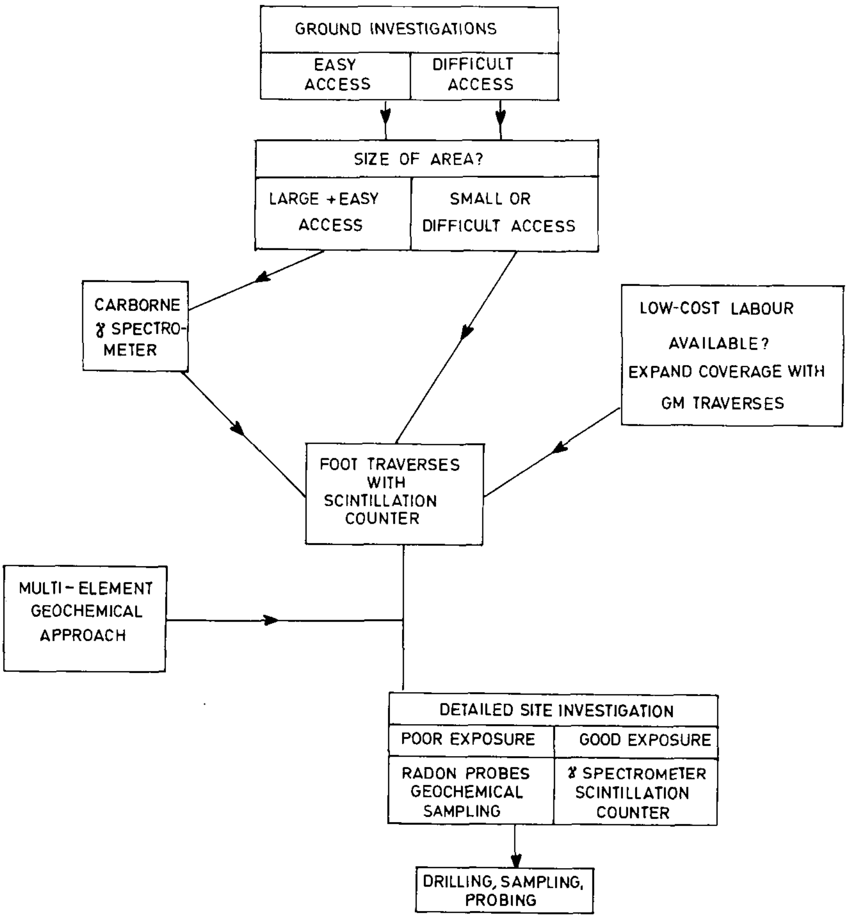


FIG. 4. Stage III: Target identification and examination based on radiation surveys.

3. COMPARATIVE ASSESSMENT OF EFFECTIVENESS OF EXPLORATION METHODS

SECRETARIAT REQUEST TO THE PANEL

It can be argued that an assessment of how discoveries have actually been made in the past would benefit any discussion of future recommendations and trends in uranium exploration.

In 1969, the Agency sent out a questionnaire to its Member States on the history of uranium exploration within their territories and included the following question on discovery methods.

> "What prospecting method was principally responsible for the discoveries made?"

Twenty-two countries completed the question, but from the five main uranium producing countries (Australia, Canada, France, South Africa and USA) only the USA included a reply.

Tabulations of the information received are given in Table I (totals and averages for 21 countries) and Table II (17 Western States of the USA).

The 21 countries included Argentina, Brazil, Gabon, Italy, Niger, Portugal, Spain and Sweden. It is apparent that different definitions of "anomaly", "prospect", "deposit" and "ore tonnage" had been used, as well as the definition of what constituted a discovery and at what stage in an exploration program a "discovery" was defined. Nevertheless, the figures are given for what they are worth.

It is recognized that this is a very crude and incomplete assessment of effectiveness of exploration methods but the Panel is invited to comment and advise on whether further work of this nature should be done and in particular on the following:

(a) Is an assessment of this type valid and useful?
(b) Would the Panel recommend that a more complete survey of this nature, including greater geographical coverage and further sub-divisions of the discovery methods, be attempted?
(c) Can the Panel advise on the type of data which would be of material help in planning future exploration programs?

TABLE I. PROSPECTING METHOD, DEPOSITS AND TONNAGE U_3O_8 DISCOVERED

Totals and Averages for 21 countries, excluding the major uranium producing countries (Australia, Canada, France, South Africa, USA)

Survey method	No. of anomalies	No. of prospects	No. of deposits	Tons U_3O_8	Ratio Anomalies/Deposits	Ratio Tons U_3O_8/Anomalies
(a) Aerial survey	3402	109	37	60 480[a]	92	17.7
(b) Carborne survey	4744	98	72	8050	65	1.7
(c) Other methods						
(i) Ground prospecting	2388	216	133	38 614	18	13.1
(ii) Geochemical	551	30	7		78	
(d) Drilling	199	9	7	6 000	28	30.0
Totals	11 284	462	256	113 144	44	10.0

[a] Includes 46 000 tons U_3O_8 in Niger.

TABLE II. PROSPECTING METHODS, DEPOSITS AND TONNAGE U_3O_8 DISCOVERED

17 Conterminous Western States of the USA

Survey method	No. of anomalies	No. of prospects	No. of deposits	Tons U_3O_8	Ratio Anomalies/Deposits	Ratio Tons U_3O_8/Anomalies
(a) Aerial survey	4000	500	120	30 000	33	7.5
(b) Carborne survey	1000	100	10	1000	100	1.0
(c) *Other methods* Ground and geochemical	55 000	2500	340	70 000	162	1.2
(d) Drilling	40 000	900	230	300 000	174	7.5
Totals	100 000	4000	700	400 000	143	4.0

PANEL REPORT

The Group has serious doubts about the validity of an assessment based on statistical information such as has been attempted. As the Secretariat itself has pointed out, considerable difficulties related to definitions are inherent in this type of compilation. It is suggested, also, that the data included in the summary of questionnaire returns relate principally to the long-established radiometric methods of prospecting and therefore represent a statistical bias in favour of these. It will be some years before experience of the less direct prospecting methods, such as geochemical and radon surveys and newer developments of radiometric techniques, allows a reasonable comparison and, as the targets of the future will be more difficult to detect, such a comparison may never be valid.

The Group does not, therefore, recommend the continuation of this type of survey and tends to the view that comparisons of effectiveness are not amenable to quantification. The selection of a prospecting method, or combination of methods, depends on several factors, including the nature of the terrain, access, road density, climate, geology and financing. A particular approach in one area may be unsuitable in another. At the "wildcat" stage of reconnaissance, at which there is no reason to suppose that uranium deposits exist in an area, general recommendations can be made for the use of rapid, low-cost methods and the choice appears to fall between widely spaced total gamma airborne surveys and reconnaissance geochemical sampling, particularly hydrogeochemical surveys. In areas in which there is strong geological evidence of favourability, the basis for selection becomes wider and the most suitable method to meet the particular geological and environmental circumstances is selected.

The Group, therefore, concludes that the most useful type of information which can be obtained for the purpose of planning future exploration programs is in the form of fully documented case histories. These should include the basis on which particular methods have been selected, the success or failure of the surveys and an assessment of the reasons for this. The Panel therefore advises the Agency to take steps to obtain such data from governmental organizations and commercial companies and to consider the possibility of publishing assessments of the individual approaches adopted.

4. EXPLORATION COSTS

SECRETARIAT REQUEST TO THE PANEL

When assisting developing countries in planning uranium exploration programs, it is found that advice on exploration costs is frequently sought. It is fully recognized that costs vary widely depending on many non-human factors: geographic, climatic, geological, etc.. Nevertheless, it would be useful if the Panel could agree and define a series of cost and time ranges for the various recognized exploration methods under average conditions of topography and climate for the year 1972. The Agency would then propose to publish these figures with suitable qualifications for abnormal conditions and it is hoped that they would serve a useful function as guidelines to organizations in developing countries.

PANEL REPORT

The Panel endorses the Secretariat's view that there would be considerable value to developing countries planning uranium exploration programs if realistic costs of exploration methods under a range of environments could be published. The Panel sub-committee charged with this responsibility has therefore prepared Table I following the format suggested by the Secretariat. The figures listed pertain mainly to North American experience.

TABLE I. COSTS OF URANIUM EXPLORATION METHODS

Method		Instrument cost and cost per unit distance and area covered: Normal low	Normal high	Distance or area covered per unit time: Normal low	Normal high	Total cost of an average minimum program	*Effective* coverage of area; comments
I. Geological mapping	Instrument	-	-	-	-	$ 10 000 for 1000 km	Total coverage may be achieved. Rate depends on method adopted.
	km	-	-	-	-		
	km^2	$ 5.00	$ 10.00	10 km^2/d (reconnaisance) 0.5 km^2/d (detailed)	500 km^2/d (reconnaisance) 10 km^2/d (detailed)		
II. Ground surveys by portable GM and scintillation counters	Instrument	GM: $ 200 Scint: $ 355	GM: $ 600 Scint: $ 1400	-	-	$ 3000 for instruments plus labour and transportation; minimum program: 10-20/km^2	100 gm-cm rock and soil. 1-5 m each side of traverse line.
	km	$ 5/km	$ 10/km	5 km/d	10 km/d		
	km^2	$ 50/km^2	$ 400/km^2	0.25 km^2/d	1 km^2/d		
III. Gross-count (total-count) carborne surveys	Instrument	$ 4000	$ 8000	-		$ 10 000 for instruments; minimum program: 3000-5000 km or 500-1000 km^2	100 gm-cm rock and soil. 5-10 m each side of traverse line.
	km	$ 0.50/km	$ 3.00/km	50 km/d	300 km/d		
	km^2	$ 5.00/km^2	$ 30.00/km^2	5 km^2/d	30 km^2/d		
IV. Gross-count (total-count) airborne surveys	Instrument	$ 12 000	$ 60 000	-	-	$ 50 000	150-m-wide belt.
	km	$ 3.00/km	$ 6.00/km	600 km/d	1200 km/d		
V. Portable and carborne gamma-ray spectrometer surveys	Instrument	$ 3000	$ 15 000	-	-	$ 8000 for instruments and one month operation	5-10 m each side of station.
	Point stations	$ 3.00/station	$ 6.00/station	10 min/station	20 min/station		
VI. Airborne gamma-ray spectrometer surveys	Instrument	$ 30 000	$ 400 000	-	-	$ 200 000	150-m-wide belt.
	km	$ 7.50/km	$ 25.00/km	600 km/d	1200 km/d		
VII. *Radon measurement surveys in* soil and sub-soil	Instrument	$ 1500	$ 6000			$ 3000 for equipment $ 300 - $ 350/km^2	1 m diameter – often less in clay or wet soil. Upward diffusion of radon in soil probably limited to 5-10 m.
	Samples	$ 1.00/sample	$ 15.00 sample	10-20 samples/d	100-300 samples/d		
VIII. Radon measurement surveys in water	Instrument	$ 3500	$ 6000			$ 5000 for instruments $ 15 - $ 30/km^2; probably a minimum program would cover 300 km^2	Limited to well-drained areas (streams) or areas with abundant surface water (lakes). Strictly a reconnaissance method.
	Collection	$ 5.00/sample	$ 30.00/sample	10 km^2/d 10 samples/d	300 km/d 150-200 samples/d		
	Analysis	$ 1.00/sample	$ 3.00/sample	10 samples/d	150 samples/d		

IX. Geochemical surveys (stream or lake sediment)	km^2	\$ 6.00/km^2	\$ 35-40/km^2			Depends on access, labour and analytical costs. A 100-km^2 program might cost \$ 2000	One sample per 1-2 km^2 gives good coverage. Provides possibility of multielement survey at increased analytical cost. Requires reasonable drainage but need not have flowing water. A reconnaissance or semidetailed method.
	Collection	\$ 5.00/sample	\$ 30.00/sample	10 samples/man/d	30 samples/man/d		
	Analysis	\$ 1.00/sample	\$ 3.00/sample				
X. Geochemical surveys (soil)	km^2	\$ 2000/km^2	\$ 5000/km^2			Normal small program would cover 1 km^2, provide 700 samples and cost approximately \$ 3000	Density depends on size of target expected. Normal sample density 30 x 100 m for vein-type or massive deposits. May be spread for large targets or in residual soils. Usually a detailed method. Can be combined with other techniques at the same time.
	Collection	\$ 500/km^2	\$ 3500/km^2	20-30 samples/d	100 samples/d		
	Analysis	\$ 1500/km^2	\$ 1500/km^2				
XI. Hydro-geochemical surveys	km^2	\$ 6.00/km^2	-			Minimum program would cover 300 km^2 and cost \$ 4000	Very definitive if the area is well-drained. Use only as a reconnaissance technique to test a large area. Depth penetration often very good.
	Collection	\$ 5.00/sample	\$ 30.00/sample	10 samples/d	150-200 samples/d		
	Analysis	\$ 1.00/sample	\$ 3.00/sample	-	-		
XII. Geobotanical surveys	-	-	-	-	-	-	-
XIII. Other geophysical methods (non-radiometric)	Instruments	\$ 10 000	\$ 50 000			\$ 25 000	Indirect. Not specific for uranium.
	Samples or readings	\$ 100/sample	\$ 1000/sample	20 samples/d	100 samples/d		
XIV. Exploration drilling (including logging) (a) Rotary	Metres	\$ 1.50/m	\$ 6.00/m	150 m/d	300 m/d	\$ 50 000	Depth and close or wide coverage of areas depending on hole spacing.
(b) Diamond drill (8-h shift)	Metres	\$ 15.00/m	\$ 60.00/m	7.5 m/d	25 m/d	\$ 100 000	

5. FUTURE RESEARCH AND DEVELOPMENT

SECRETARIAT REQUEST TO THE PANEL

The Agency sponsors and supports research under Research Contracts and under Research Agreements. The former is normally arranged with institutes in developing countries and carries a modest financial award. Research Agreements carry no financial award and are more frequently arranged with institutes in the more developed countries. In certain instances it is recognized that it would be desirable for a number of institutes in different countries to collaborate on different aspects of a specific research problem and this may be done by the Agency's employing both Research Contracts and Research Agreements together in a Co-ordinated Program.

Panel members are invited to consider any research work which they believe could usefully be done to facilitate future uranium exploration and which the Agency might be able to assist through Research Contracts, Research Agreements or through a Co-ordinated Program.

PANEL REPORT

It is probably true to say that there is no method or technique applied to uranium exploration which does not merit further research and development. Priority should obviously be given to those techniques which have been less widely applied but which show promise of being effective, in particular those which are likely to aid the early identification of new uranium provinces and/or indicate the existence of deposits not readily detectable by direct surface radiometric monitoring. Nevertheless, the advances which have taken place, and can be expected to continue, in the miniaturization of electronic circuits and the improvement of instrument reliability suggest that the efficiency of all instrumental techniques can be increased by developments in the design and construction of instruments, even the simplest type of total radiation monitor. Such technical developments may offset the higher cost of features, such as hermetic sealing, which are desirable in instruments to guarantee reliable operation in the widest possible range of temperature and humidity conditions.

Specific techniques for the purposes of research and development can be conveniently divided into two categories:

(1) Well-established techniques
(2) Techniques which have not to date been used on an appreciable scale or even tested under experimental conditions.

(1) In the first category the following developments can be identified.

Airborne survey data research and development. While the present method of measuring radioactivity by means of scintillation counters may not be ideal, there does not appear to be any possibility of the development of an entirely new principle of measurement in the foreseeable future.

The value of data produced by existing systems could, however, benefit by the recording of complete gamma spectra. The development of such facilities could best be based on an existing sophisticated instrumental capability, including a flying platform and data handling system, such as that of the Geological Survey of Canada.

Research and development in on-site geochemical measurement. A number of Panel members have emphasized the value of being able to undertake rapid and reliable analyses in the field and the recurring recommendation that multi-element surveys are a concomitant of uranium geochemical surveys indicates the desirability of the development of combined analytical techniques. There are obvious operational advantages in such analytical facilities being based on instrumental methods; and in view of the common electronic systems involved, a combination of gamma spectrometric and X-ray fluorimetric analytical techniques would seem to be a rational development. A sufficient number of Governmental and private laboratories are already engaged in the development of chemical and instrumental techniques to suggest that progress can be made by the establishment of Research Agreements initiated by the Agency.

Research on geochemical processes in the weathering cycle. There is a continuing need to improve basic knowledge of the geochemical processes influencing the migration and redistribution of uranium in the supergene environment under a variety of climatic and geological conditions. One specific area of study is the partitioning of uranium between water and the products of hydrolysis. For example, an answer to the problem of why bauxites are always enriched in uranium with respect to the parent rock would provide useful interpretative data. The behaviour of uranium under tropical weathering conditions must be of particular interest to some developing countries and the apparent absence of geochemical haloes in such environments is an example of a specific problem which should be investigated. Spurious anomalies, e.g. associated with laterites, present difficult problems of interpretation and research to determine whether or not they can be of value in exploration would be desirable. Allied to this type of research is that involving the analysis of geochemical effects (mineral destruction, changes in mineral form) associated with the movement of mineralizing solutions.

Bedrock geochemistry. The fundamental basis for the interpretation of all applied geochemical data is the distribution of elements in bedrock. Modern automatic analytical systems are now capable of generating large volumes of data and those of particular reference to uranium exploration, e.g. the bedrock concentrations of uranium itself, could be usefully collated for publication.

Research on radon and other gaseous diffusion. There is a general need for research into systems of soil gases to improve understanding of the relationships between radon and its parent uranium source and also to investigate the potential of applying data on the ratios of radon and other soil gases (helium in particular) in uranium prospecting.

Development of instrumentation for radon detection. The principal problem of all the more commonly employed methods of radon measurement is contamination of the detector by decay products. The solution to this, possibly involving the development of alpha spectrometry, represents a profitable subject of research in this field, in terms of potential improvements in efficiency and precision.

(2) Recommendations for research and development on relatively untried techniques include the following:

Radiogenic lead. Isotopic determination of radiogenic lead in non-radioactive minerals may be a means of identifying a favourable area for uranium at the reconnaissance stage. Deficiencies in radiogenic lead in uranium vein minerals may be attributable to the diffusion of radon from the system and an enrichment of radiogenic lead in rocks and superficial deposits might be expected to occur over uranium deposits. Research is necessary to establish whether this lead is detectable initially in samples from the vicinity of known uranium deposits, so that the size of the dispersion haloes could be determined.

Radiogenic heat. Opinions within the Panel differ regarding the potential value of measuring temperature differences as a means of indicating the proximity of radioactive deposits. Given the large volume of physical data which exists, it should be possible to calculate the theoretical temperature ranges to be expected from different conditions of source size and geometry, lithology and groundwater regime. Such calculations have been carried out for thermal areas and temperature differences have been shown to be obscured by meteoric water movement. However, the instrumentation exists and trials could be arranged in areas in which the method has the most likely application.

Sulphur-isotope determinations. The possibility of identifying, with the aid of sulphur-isotope data, the source of sulphur in various natural sulphur-bearing substances provides an opportunity for using sulphur-isotope analysis as an exploration tool. It has been applied to the search for roll-type deposits in the sandstone environment of the USA and, as the necessary isotope analytical services are available on a commercial basis, future research involves only the wider application of the method to other regions. The Agency could encourage this research by way of Research Agreements.

Remanent magnetism. The possibilities for using this method to distinguish between iron oxides formed as a result of alteration associated with uranium-ore deposition in sandstones and iron oxides unrelated to this process would seem to justify appropriate research with a view toward development of exploration applications.

Airborne geochemistry. (a) Measurement of the concentration of ^{222}Rn in air below atmospheric inversion layers holds promise of rapidly detecting areas, even of quite small dimension, in the course of airborne surveys. Testing of the method involves the development of a suitable

ionization chamber. (b) Collection and measurement of solid radioactive decay products attached to aerosols in the atmosphere is a technique which might be readily incorporated in existing airborne survey systems for trials.

RECOMMENDATIONS

The Panel is conscious of the very large amount of effort, in terms of equipment and manpower resources, involved in meeting the research and development needs outlined and the limited financial resources available to meet them. It suggests that the Agency, apart from any direct support it is able to provide in the form of Research Contracts, has a most important role to play in encouraging R & D by offering a medium for the publication of papers on specific research projects.

Recommendation I

That the Agency encourages publication of research work in its own publications.

Recommendation II

That the Agency continues to maintain a watching brief on modifications and developments of existing instrumentation and on developments of new techniques with a view to disseminating the information; and that it attempts to identify those organizations involved in developments likely to result in the production of new instruments and to arrange appropriate Research Agreements.

Recommendation III

That the Agency plays an active part, through the medium of Research Contracts and Research Agreements, in supporting specific items of basic geochemical research, including that on soil gases.

Recommendation IV

(a) That the Agency encourages and facilitates the collection of samples of uranium ores and associated minerals from uranium deposits throughout the world.
(b) That the Agency provides financial assistance or suitable facilities for the maintenance of such collection, either at the Agency or elsewhere.
(c) That an adequate system of control of the distribution of such materials for research purposes be established.
(d) That the Agency accept the role of arranging for the provision of research sample material to requesting nations from donor nations.

Recommendation V

That the Agency consider means of making available to developing nations lacking appropriate R & D facilities those analytical services, available in other countries, for which they have a need in their exploration programs, such as, for example, age determination and isotopic analyses.

6. PROSPECTS FOR URANIUM IN APPARENTLY UNPROMISING ENVIRONMENTS

SECRETARIAT REQUEST TO THE PANEL

In April 1970 the Agency convened a panel meeting on Uranium Exploration Geology. The emphasis at that meeting was in defining, largely on the basis of accumulated evidence, favourable environments for the occurrence of uranium deposits, and comparatively little attention was given to untested environments.

The present Panel is invited to consider untested geological environments which, up to now, have been assumed to be unfavourable for the occurrence of uranium, and to make recommendations on whether research should be done on the problem and, if so, what type of research.

PANEL REPORT

Exploration and research priorities should rightfully be accorded geological environments that on the basis of past experience show greatest promise for economic deposits of uranium. On the other hand, the less promising or apparently unpromising environments should not be dismissed from consideration, particularly if there is reason for suspecting on theoretical grounds alone that uranium might accumulate by any of the various geochemical processes considered to be operative in these environments. For example, approximately one-third of the uranium reserves of all nations of the world, excluding the USSR, Eastern Europe and China, occur in fluvial sandstones and are probably attributable to deposition by biogenic hydrogen sulphide. Some consideration ought therefore to be given to the possibilities for uranium in other sedimentary environments containing stratabound metallic deposits supposedly precipitated by biogenic H_2S.

The subcommittee on prospects for uranium in apparently unpromising environments has the following recommendations to make.

(1) That the title of the subcommittee be modified to "Prospects for uranium in apparently unpromising environments" from the original title, "Exploration prospects in untested environments". It is the consensus of this committee that most types of geological environments, including mineral deposits, have been tested to some extent for uranium and that some environments have been found to be favourable whereas others appear to show less promise based on exploration experience to date.

(2) That the following be included among those environments considered to be apparently unpromising in light of current exploration experience.

   (a) Plutonium rocks cther than granitic rocks
   (b) Basaltic extrusives

(c) Marine environments, with the exception of marginal marine sandstones
(d) Aeolian and glacial sediments.

(3) That among the environments of lesser rank the following be included at this time as relatively unpromising for occurrence of economic uranium deposits.

(e) Coal deposits, with the exception of lignitic coals in some areas of the world
(f) Limestones
(g) Shales, with the exception of certain alum shales and copper-bearing shales
(h) Evaporite deposits
(i) Deposits of a large number of metals including zinc, lead, manganese; deposits of certain metals may form under chemical conditions that are also conducive to the precipitation of uranium, and these may justify additional attention, e.g., copper which occurs with some economic uranium ores with which uranium occurs as a by-product.

(4) That by-product sources of uranium be excluded from consideration by this committee.
(5) That the Agency investigate the joint UNESCO-IUGS program involving international geological correlations that may exist between geological environments and the occurrences of ore deposits. That the Agency explore the possibilities for collaborative efforts with the International Geological Correlation Program (IGCP), after this program is approved by the General Conference of UNESCO.
(6) That the Agency solicit information from all nations regarding the extent to which examination for uranium has been made in deposits of other metals, non-metals, and other environments identified herein as "apparently unpromising"; furthermore, that all noteworthy occurrences of uranium in these environments be brought to the attention of the Agency and, subsequently, this committee with a view toward further dissemination of information in subsequent Agency reports.
(7) That the Agency recommend that uranium be included in exploration programs for other metals wherever such programs are being undertaken, particularly within less developed nations.
(8) That the Agency give relatively low priority to physical exploration in rocks identified as unpromising but that a watchful attitude be adopted; only theoretical consideration should be given to these environmental types at this time, and continuing examination of possibilities is suggested.
(9) That the Agency arrange, through appropriate contracts, for the compilation of all existing background data on the uranium contents of various rock types throughout the world as a basis for recognizing anomalous conditions wherever they may arise. That this might very well be included under research and development considered in Secretariat Document No. 5.

7. POLICY OF DEVELOPING COUNTRIES IN REGARD TO URANIUM EXPLORATION

SECRETARIAT REQUEST TO THE PANEL

Over the last two decades many developing countries have shown an interest in uranium exploration. Some programs have been small and relatively unsuccessful while other countries have successfully proven substantial ore reserves. Some programs have been entirely national, others have received international or bilateral assistance, or private enterprise arrangements have been made. The International Atomic Energy Agency has, for example, assisted over 30 countries with their uranium exploration programs during the last 12 years.

In a difficult and confusing situation (past, present and future), with regard to nuclear power and uranium supply and demand, developing countries have encountered problems in defining their objectives and policy on uranium exploration programs.

The Agency's advice has been sought on whether a country should search for indigenous uranium resources, the possible benefits to the national economy to be derived from proving up its own resources, the appropriate size and costs of such a program, the role which aid and contractual arrangements might play, etc.

The Panel is requested to consider these matters and to advise the Agency on the policy which might be recommended to developing countries in regard to uranium exploration.

DISCUSSION (EXTRACTS ONLY)

H. H. ADLER: Is the problem one of assisting a developing country or of finding uranium to meet the world's future requirements? I thought the target was primarily to make sure that there is enough uranium to meet energy needs for the future and that the developing countries can assist in this goal. We can set forth or prescribe for them certain ways in which they can help fulfil this ultimate goal. Whether they make use of the nuclear energy resources directly or whether they sell nuclear resources to nations that need them and which in turn can return money to such countries to spend in other directions is not our concern. They do, however, have a role here, because I believe that quite a considerable amount of the world's area is in the developing nations and exploration would be extremely useful in these areas.

R. D. NININGER: That thought has occurred to me and I was dissuaded from speaking because of an earlier comment that the Agency does not "promote". But now that I think about it, the Agency was created to promote the development and use of atomic energy and, of course, Secretariat Request No. 1 and my introductory paper did point up the problem of a potential lack of adequate resources, not for individual countries, but for the world. In the light of that, perhaps it is not correct to say the Agency should not promote. If the Agency is aware, or if we as one of the consulting groups to the Agency are aware, that a particular developing country

seems to have the favourability for developing an important supply of uranium, we should help identify these places and help the country or in some way inform the country that this is the case. Maybe, this opens up a whole new thought, but I am glad that Mr. Adler did bring it up and I think it should be considered.

H. BRAND: Mr. Adler's question is an interesting one. Are we here to advise the developing countries, or are we here to promote the discovery of new sources of uranium? It is a question of economics again. The developing countries, just like the developed countries, will develop a resource if there is a market for it. If the developed countries do not find it economic to produce uranium because the demand is not demonstrably there, I do not think the developing countries are going to do it either. To the extent that they are producing it for export, uranium is simply another raw material to be exported to earn foreign exchange. If there is a market for uranium and they feel that they have got some sources of uranium that they can develop and sell, they will do that. However, if they think that it would be better for them to look for other minerals that they can sell more easily, they are going to look for, say, copper or whatever else they can sell.

A.G. DARNLEY: Which do we consider first? The self interest of the individual countries or the greater need of the international community? Should we look first at the needs of a developing country, what it possesses, what it lacks, what it should be spending its money on, or should we look at the need in 20 years time of, say, the countries of Western Europe for uranium raw materials. Where are we putting the weight in this matter?

D. OSTLE: Mr. Darnley is right, but there need not necessarily be a conflict between these two requirements.

H. BRAND: I agree there need not necessarily be a conflict but insofar as there is, you can be perfectly sure which choice any country will make; national self interest always comes first. There is no point in telling them it may not suit their own national interests but that the world needs it.

H. H. ADLER: I cannot envisage any country turning down any reasonable opportunity for financial assistance to discover even a resource that will perpaps, if not today, be brought into production in the future. Secondly there is also the economic consideration that the discovery in a developing country could bring to the forefront uranium that can be produced more cheaply than in other countries and therefore it does constitute an immediate economic reserve for that country simply because it is highly competitive as far as price is concerned. For example, if a country were to discover another Shinkolobwe-type ore body making up 50 000 or 100 000 tons of uranium, it cannot help but be put in a better economic state as a result of it because the mining companies would be in there attempting to develop those resources before they develop the higher cost resources. So I do not think that is a consideration.

H. BRAND: Mr. Adler said that he cannot visualize a country not accepting aid to look for uranium but somebody has got to offer them that aid. As far as the UNDP program is concerned it is limited; they have to make a decision on scarce means and alternative ends. If, on the other hand, an industrially developed country were to go to a developing country and say, here is X million dollars to look for uranium, I am sure it would not turn it down, but it does not happen that way. Developing countries have to decide on what they are going to spend their limited aid and at this stage I do not think uranium looks particularly inviting vis-a-vis other

resources. If they are going to be given the aid specifically to look for uranium, of course they will take it, why not?

R. D. NININGER: I would like to make two points on that. First, I do not think that the present soft market for uranium is a reason to say that uranium is not an attractive investment. By the time any developing country could start a new exploration program, find uranium in economic quantities, develop it and bring it into production, we will be at the point in time where everyone seems to agree that the demand will exceed the supply we can now see. I think it is perfectly valid to make that point to developing countries. My second point is that I did not mean to try to encourage developing countries or push them into a choice of spending their limited funds one way or another, but merely to make available general information which would indicate that in a particular case there was the favourability for uranium and with that knowledge they could then make a better choice as to whether they wish to go further or not.

H. BRAND: I just want to make it clear that I am not saying that I do not believe there is going to be a big demand for uranium. All I am saying is that one has to convince the developing countries in the same way as you have to convince the mining companies in the developed countries to go ahead and invest in this sort of thing. You do not have to convince *me*, but *they* have to be convinced and until they *are*, it is the same simple market forces that operate. If they are convinced that there is going to be a strong market for uranium and if they do have demonstrated uranium resource possibilities, I think that they will go ahead and develop them.

H. H. ADLER: I suppose it would be appropriate for the Agency to take a role in this direction; after all it was suggested that we educate the financial world regarding the future uranium situation. Maybe we ought to take the same part with regard to the developing countries and educate them in some manner as to the future needs for uranium.

R. D. NININGER: My wish is that we do nothing to dissuade developing countries from considering the potential importance of uranium exploration. If we indicate too much the requirement for assessment of all the alternatives, this may suggest that they should not go in for uranium exploration.

S. H. U. BOWIE (Chairman): The overall energy and mineral resources of a particular country may not be the most important consideration. They may decide that they wish to develop uranium for export and I do not think that this Panel ought to discourage that; after all, we are saying that there may be a shortage of uranium on a world basis if we do not do something about it. If there were a very favourable environment for uranium, maybe the developing country ought to be encouraged to go ahead, perhaps under an aid program.

H. BRAND: Whether the Panel is really concerned with the world energy situation is a debatable point, because I think the terms of reference of this Panel are fairly closely defined. However, one does tend to introduce an element of artificiality if one tries to divorce oneself from the world energy picture, because surely the projections of uranium demand are related to the world energy picture. Supposing there was a tremendous breakthrough in some other source of energy, all these predictions mean nothing. I am not saying that this is going to happen, but one has to take all these possibilities into account. I think that one can define the purposes of this meeting anyway one likes, but I think one leaves oneself open to the

criticism that one is trying to operate in a vacuum if one ignores the other facts of life, one of which is the world energy situation.

R. D. NININGER: I wonder whether you would allow me to read a few sentences from what I would call the Panel's charter, which we all received when we were invited to come. Right at the top it stated "Panel on Uranium Exploration Methods". In parantheses under that it says "with a special reference to the developing countries" and it begins by saying "Forecasts of uranium requirements until the end of the present century show a very large and increasing annual demand from the late 1970s onward. Although recent discoveries and the present substantial reserves have currently induced a soft market, the longer-term requirement for new uranium is very great. Because of this situation, concern has been expressed about any cutback of exploration which may take place in the next few years and it is believed by most authorities that, on the contrary, this is the time to plan how and when exploration should be intensified". So the whole charter of the meeting is directed toward a potential problem that is foreseen, and what should be done about it, and with particular reference to developing countries.

S. H. U. BOWIE: What we are saying is that there is a risk of a shortage of uranium over the years unless adequate steps are taken to search for new deposits, to find them and develop them. It is the Agency's function, as I see it, to make this known to the developing countries as well as to any other country. It is within the field of our competence to make this kind of statement on the basis of the information available on requirements. I think that is what we can do here and, if we feel that encouragement should be given to developing countries when there is a good favourability for uranium being discovered, then this is something we could do and something we could stress. To this extent I think that we are perfectly entitled to say that we encourage developing countries to undertake reconnaissance for uranium, particularly if the geological conditions are favourable. If they are completely unfavourable in the opinion of informed experts then perhaps the opposite ought to prevail, they ought to be slightly discouraged from wasting money. But I think that this is where the Agency and the experts available to the Agency have an important role to play. The Agency could give assistance to developing countries in the search for uranium not only in indicating whether this is a useful thing to do in their particular terrain but to indicate the most appropriate techniques for use, what it would consider to be a viable team and the approximate amount of money that has to be spent to establish a reasonable tonnage of ore. There is not much point in a country looking for uranium if the chances are that it is only going to come up with 200 or 300 tons at the end of a 5-year program. The other thing I think that we could do is to indicate that the Agency could also give advice, after the reconnaissance stage through the follow-up stage, in providing assistance in calculating reserves. This is something that a lot of us have had a great deal of experience in and I think that we have seen evidence in recent years of rather poor attempts being made at the establishment of reserves. I think this is where the Agency, with its experts at hand, can play a very important role.

J. CAMERON: The Agency, through hiring experts, certainly responds to helping with the evaluation of ore deposits. We already do this. It all depends on the type of request that comes in. When we get a request, admittedly we sometimes ask for it to be revised in the light of our own

knowledge, but once it has been framed by a country, we respond to it within the limits of our resources and it can cover almost anything from initial advice on whether the geology is favourable, right through to the evaluation of ore reserves.

R. D. NININGER: If I may revert to an earlier part of the discussion, I was a little concerned about the coupling in the Secretariat's Request of what could be construed to be two opposing ideas; (1) find uranium for one's own national program and (2) find uranium for the income one will realize. A uranium exploration program could begin for the purpose of developing an indigenous source but, without any particular planning it could, if successful, go much further and become both an indigenous source and a source of income through export. Perhaps we are complicating the problem by exaggerating this idea of two alternatives. I would agree that there are countries that will wish to develop uranium even if it is not economical as an export, but that is rather a side issue. My general comment, too, was that for a panel convened to discuss exploration methods and given the charter to which I referred before, there is a major exploration job to be done and we are discussing what to do about it. Since we are dealing with uranium and not with the whole subject of mineral exploration or energy or all types of energy fuels, then, only if there were strong reasons, on the basis of the Agency's experience, that is to say some evidence that a large number of countries are completely off-base and doing things they should not be doing, should we really step out of our major role and issue a warning. Unless there is such a situation, I am not quite clear why we should even address ourselves to the subject in this manner. We have, through the other papers and documents and through the papers given by the members of the Panel, and through the discussion, explained and presented a body of information which developing countries can look at and consider and can then decide what they might do, acknowledging that the assistance of the Agency, bilateral assistance, or company assistance is available.

S. H. U. BOWIE: Thank you, Mr. Nininger. I think this seems to be the view of several people here. I feel that what we should be doing here is to assist the developing countries in reaching their full potential with respect to uranium resources and we should try and indicate to them how best to go about this in relation to a uranium exploration program. I think we should perhaps try to produce a document for the developing countries along those lines, bearing in mind the objections that have been made to us getting into the pseudopolitical sphere and also to including other energy resources, which is not really our function. I would like to recommend that the Secretariat take into consideration the various viewpoints that have been expressed, when presenting the paper we will draft.

PANEL REPORT

(1) The Panel recognizes that every country requires energy and mineral resources and every country, developed and developing, should possess an energy resource policy based on its anticipated future needs and on an inventory as complete as possible of its own natural resources.

(2) Uranium should be regarded as both an energy resource and a source of income and considered within the same framework as other energy and income-producing resources. Policies with respect to uranium use, exploration and exploitation should be governed by economic considerations similar to those for other potential sources of energy and income.

(3) If insufficient evidence is available to enable reasonably reliable preliminary conclusions to be drawn concerning the mineral resources of a country, steps should first be taken to make some evaluation of the resource potential, utilizing, where appropriate, modern mineral survey techniques.

(4) When balanced information about the energy and mineral resources of the country is available, decisions can more usefully be taken about whether to make an intensive search for any particular resource such as uranium.

(5) The Panel recognizes that developing countries could benefit in two different ways if uranium deposits can be found within their territories;

(a) By utilizing national uranium in national nuclear power stations
(b) By commercial export sales.

(6) The question as to whether a country should develop uranium resources for internal consumption as against external sale must be considered in the light of priorities for other sources of power and other sources of export income.

(7) The Panel recognizes, however, that these need not be opposing concepts. A uranium exploration program could begin for the purpose of developing an indigenous source, but it could, if successful, go much further and become both an indigenous source (of energy) and a source of income through export.

(8) The situation for every country at any given time must be assessed using the best evidence available to it. These are essentially economic decisions which must be guided by the earth science information available to the country. The financial resources of a country should not become unbalanced by pursuing a uranium program, if the overall economic consideration of the possible alternatives do not justify it.

(9) If the preliminary energy and mineral resource appraisal of the country indicates the presence, or the probable presence, of uranium mineralization, then the steps to investigate and possibly exploit this should follow the same pattern as would be applied to any other mineral resource.

(10) The Panel does, however, wish again to call attention to the magnitude of the exploration effort that will be required to meet the future world demand for uranium and wishes to emphasize that the present (1972) soft market for uranium does not mean that uranium is not an

attractive investment. By the time any developing country could start a new exploration program to find uranium in economic quantities, develop it and bring it into production, the point in time will have arrived where it appears that demand may exceed supply.

(11) If a uranium exploration program is planned, the Panel recommends that before it commences, appropriate experts, including economists, should be consulted to consider all relevant evidence and make recommendations on the following matters:

(a) Should the exploration program be confined to uranium or extend to other mineral commodities?
(b) Establishment of a budget expenditure which, while within the available financial resources, is at the same time sufficient to offer some chance of success.
(c) Determination of the number and source of trained personnel required for a program, and of their function.
(d) Minimum tonnage and grade that would warrant going beyond preliminary appraisal. While the tonnage may be as low as a few thousand tons U_3O_8 if national utilization is the objective, it may have to be many times that amount if commercial export is the objective.
(e) Whether (i) the program should be entirely nationally executed, (ii) international, bilateral, or private company assistance should be sought, or (iii) contractual arrangements for exploration and production should be made.

(12) The Panel recognizes that a country must take its own decision on uranium exploration policy and on the extent to which it wishes to use the services of expatriate assistance to develop its resources or to train its personnel.

(13) The Panel recognizes the continuing need for the Agency to assist developing countries in developing their full potential with respect to uranium resources and notes that, when requested and within the limits of its resources, the Agency can provide advice, expertise, training facilities and equipment to developing countries for all aspects of uranium exploration and development.

LIST OF SUB-COMMITTEES

1. GENERAL POLICY ON FUTURE EXPLORATION REQUIREMENTS

   R.D. Nininger, Chairman
   Members: all participants of the Panel

2. SURVEY OF PRESENT METHODS

   J.F. Davis, Chairman
   A.G. Darnley
   H. Fauth
   M. Matolín
   M. Dall'Aglio

3. COMPARATIVE ASSESSMENT OF EFFECTIVENESS OF EXPLORATION METHODS

4. EXPLORATION COSTS

5. FUTURE RESEARCH AND DEVELOPMENT

   D. Ostle, Chairman
   H.H. Adler
   A.S. Bhatnagar
   Y. Shimazaki
   E. Lukacs

6. PROSPECTS FOR URANIUM IN APPARENTLY UNPROMISING ENVIRONMENTS

   H.H. Adler, Chairman
   K. Fuzikawa
   J.A. Fernández Polo
   M. Dall'Aglio
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7. POLICY OF DEVELOPING COUNTRIES IN REGARD TO URANIUM EXPLORATION

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